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Alignment tolerances

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Contents

1 Scope

This document described the alignment tolerances for the target optical systems [1]. It describes how loss of light affects performance, the tolerance limits for the design, and simulation results.

2 Introduction

In a well-aligned system, the beam of light going from the region of interest to the camera is determined by the size of the virtual image and the camera aperture. The beam footprint grows linearly with distance. There are several apertures on the way, due to the narrow path in the PBIP and shield wall, and the size of the mirrors and the vacuum window. All these apertures are larger than the beam footprint on them. The difference between the apertures and the footprints gives a margin for absorbing errors in alignment without losing light.

The expected errors in alignment due to installation and thermal expansion is an important guide to determine the parameters of the optical system. The tolerances we have will also guide the design of the PBIP.

3 Loss of light

Light is emitted as point sources from the object, and extends as cones as the light moves toward the camera lens aperture. Loss of light occurs when an aperture that is not the camera lens aperture moves in to the beam of light. The effect of an aperture blocking light depends on the position of the aperture, as illustrated in Figure 1.

If light is lost near the object, it will very likely lead to loss of field of view.

Loss of light in the middle of the optical path will give vignetting, most likely in the form of darkening of an edge or a corner of the image. This can be corrected for, but will reduce sensitivity in the areas that are darkened.

Loss of light close to the camera lens aperture will darken the entire image. The light yield of the best known coating goes down with integrated dose. Losing light on the way to the camera will make the signal to noise ratio worse, and shorten the lifetime of the profile monitor.

If a mirror has a transverse error in translation, meaning the mirror is shifted in the plane orthogonal to the incoming optical axis, it can only cause loss of light in the translated mirror. This is a local problem.

A translation along the optical axis will lead to errors similar to transverse translations in the following mirrors, as the incoming beam will be shifted. The shift is to some extent corrected for as the entrance pupil, the image of the camera lens aperture as seen from the object, will shift as well.

If a mirror has an error so that it is tilted out of the plane of the mirror surface, it will affect the beam footprint on all the other mirrors. The position of the object as seen from the camera will move, and the position of the entrance pupil as seen from the object will move.

If the first mirror has large errors in tilt, it will not greatly affect the angular field of view, but it will shift it. If the field of view is shifted sufficiently, it will not overlap with the region of interest, meaning the beam window and fiducials.

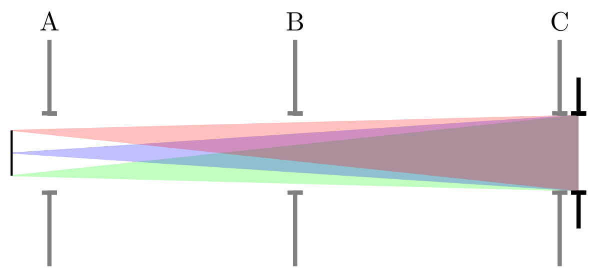

Figure 1: Light moves from the object plane on the left, to the camera lens aperture on the right. The red, blue and green cones show light coming from the top, middle and bottom of the image plane. If aperture A is shifted into the beam, it will quickly obstruct the view of the full object. If aperture B is moved into the beam, it will cause broad vignetting before any part of the object is obstructed. If aperture C is moved into the beam, the effect is similar to reducing and moving the camera lens aperture.

4 Tolerance limits

The mirrors will be aligned in the PBIP in the mock-up at room temperature. The main sources for errors are expected to be due to moving the plug from the mock-up to the target monolith, the heating of the plug during operation, and errors in the initial alignment of M1.

M2-M7 will be mounted on adjustable mirror mounts. We are expecting these mirrors to have excellent initial alignment, meaning that the mirrors will be well centered on the other apertures along the path, and that the light beam footprint is well centered on the mirrors themselves.

In order to achieve excellent initial alignment, it must be possible to reach the nominal alignment of M2-M7 within the Bendamount adjustment range [3], which is $\pm 5mm$. The mirror interfaces should not deviate from the nominal position by more than 0.3°. The interface to M1 should be within 1mm of the nominal position.

The alignment of these mirrors with respect to the PBIP should not change when the PBIP is moved from the mock-up to be installed in the target monolith. The alignment will be validated and adjusted as the PBIP is installed vertically in the mock-up.

M1 will be mounted on a mount that is not adjustable, as sufficient thermal connection to the cooled PBIP is hard to achieve with an adjustable mount. The errors on the installed position of the center of the mirror with respect to the plug should be within 1mm. The errors on the tilt of the mirrors should be within 0.1°. In order to achieve this, it may be necessary to survey the interface surface and custom make the mount. The interface surface is the machined surface of the PBIP structure made to accept the mount itself.

The error in distance from the target wheel/proton beam window to the position of M1 should be within 5mm of the nominal value.

When the plug is installed, the position of the center of the proton beam aperture in the optical slice, with respect to the object, should not move by more than 2mm in any direction. The tilt of the optical slice should be within 0.3° of the installation in the mock-up. The errors on the tilt of the plug are less severe than errors on M1. The reason for this, is that the optical axis going out from the top of the PBIP can be re-centered on the following mirrors by adjusting the tilts of M4 and M5 using the camera and the illumination system.

The heating of the plug during operation will mainly affect the lower part of the plug, where M1 will be mounted (see [2] for a preliminary study). The errors in the interface to M1 due to thermal expansion should not exceed 0.3°. The total errors in M1 due to thermal expansion, including thermal expansion of the mount and mirror, should not exceed 0.4 °. The total errors due to thermal expansion of mirror, mount and interface should be less than 1 mm in any direction.

For the remaining mirrors, errors to the tilts of the interface surfaces should not exceed 1 milliradian. M2 and M3 should not move by more than 1 mm in any direction. M3, M4, M5 and M6 should not move by more than 2mm in any direction. The reason for the difference is that the mirrors above the PBIP are less constrained in size, and will be bigger. The mirror mounts for M2-M7 are not expected to deform significantly due to heating.

The clear aperture between M1 to M2 should be no smaller than 80 mm × 75 mm. The clear aperture between the following mirrors should be no smaller than 100 mm × 100 mm.

A full simulation of the thermal deformations in the PBIP is not yet available. If the above values are not achievable, the system may need to be redesigned. To some extent the optical system can be made more robust by adjusting M1 to create a smaller virtual image, or by accepting a lower effective lens aperture. In both cases, less light will reach the camera, and the system loses sensitivity.

5 Simulation of errors

The tolerance limits have been determined based on simulations done on the model of the target wheel described in [1]. Simulations have been done using Zemax OpticStudio. The model includes mirror sizes, and the minimum clear aperture in the shield wall and the vacuum window.

The errors that have been studied in Zemax are

- Errors to the installation of the plug. This has been added as a tilt and shift of the entire optical path about the center of the proton beam aperture in the optical slice. The model assumes we are able recenter the optical path above the PBIP.
- Translations and rotations of all individual mirrors.
- Propagation distance between mirrors, representing translation errors along the optical axis.

The field of view is limited by the size of the first mirror. Errors due to the tilt in the Plug or M1 will shift the field of view. Figure 2 shows the footprint of the beam on M1 with ideal alignment. Figure 3 shows the worst case footprints on M1. The plug is rotated by 0.3° about all axes, and M1 is rotated by 0.5° (0.3° due to thermal deformations in the interface, 0.1° due to thermal deformations in the mount and 0.1° due to initial misalignment). In all cases, the full region of interest is visible, with no vignetting or loss of image quality.

In order to study the effect of all the errors listed in Section 4, Zemax OpticStudio has been used to generate optical systems with random errors within the tolerance limits. The errors are drawn from a parabolic distribution, meaning that errors close to the limits are more likely that errors close to zero. Parabolic errors were chosen over normal or uniform errors, as they give the most pessimistic results.

In order to quantify the amount of light loss, corrections to the size of the entrance pupil as seen from different points in the object have been used. A correction of 1 means that all light from the point is lost, a correction of 0 means that no light is lost. The points that are studies

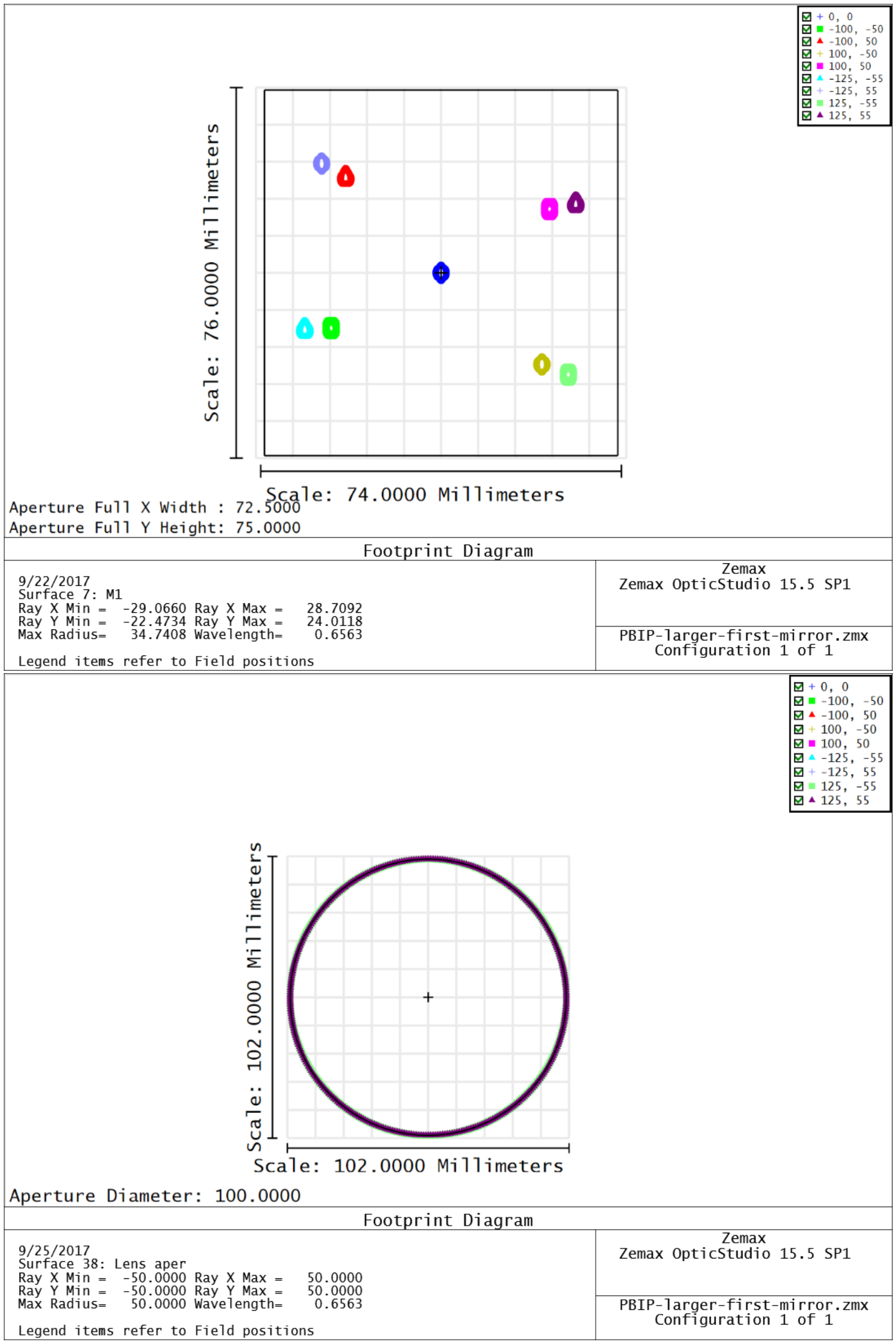

Figure 2: Beam footprint on M1 (left) and lens aperture (right). The 9 colors represent light coming from the center of the beam entrance window, the four corners of the beam entrance window, and the four corners of the area for fiducials.

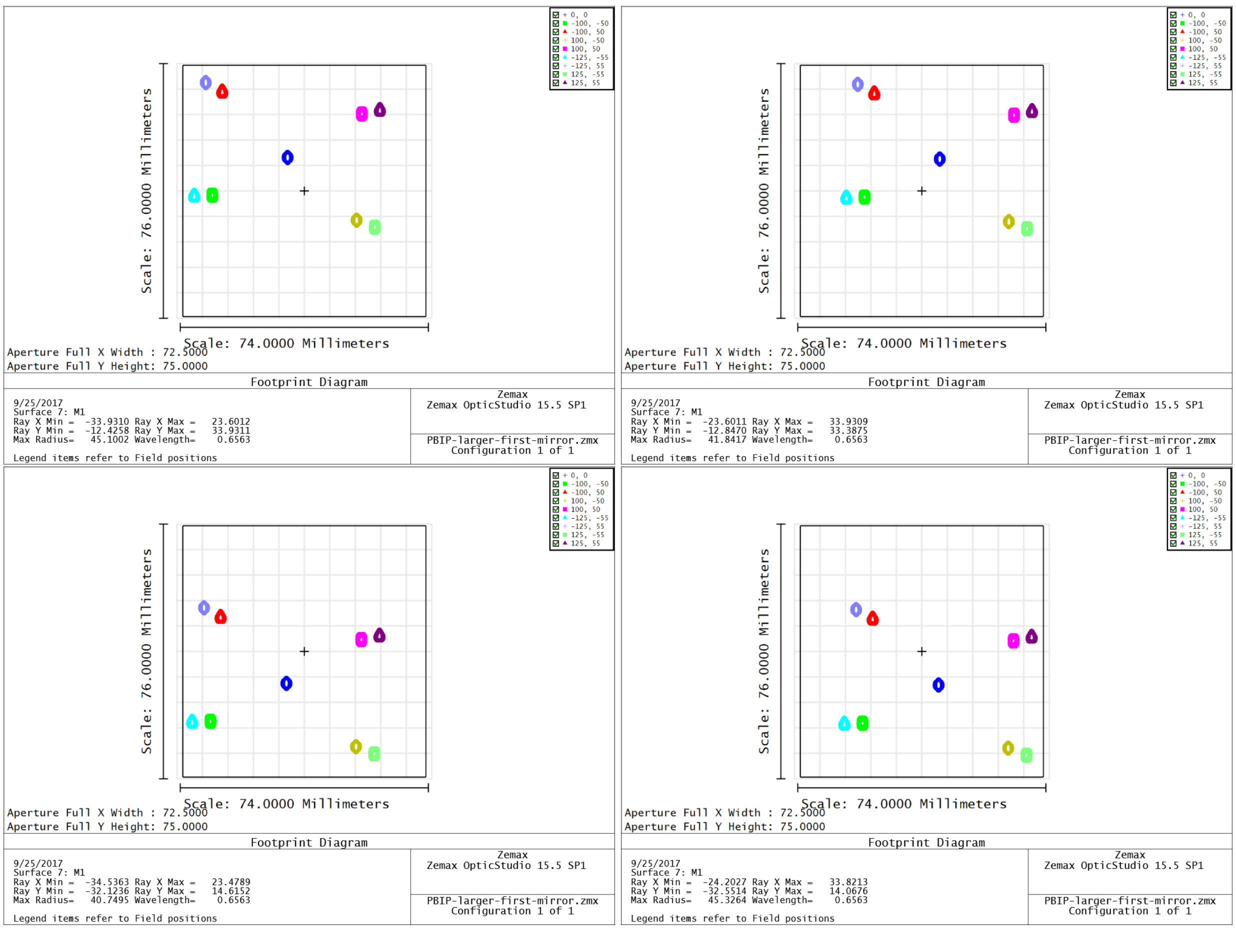

Figure 3: Beam footprint on M1 with the worst case combinations of 0.3° tilt errors on the PBIP and 0.5° tilt errors on M1. No light is lost in any of these cases.

is the center of the region of interest, as well as the corners of the beam entrance window, the correction to the pupil are simply added together.

Based on 100 monte carlo generated systems with the tolerance limits listed in Section 4, 59 systems do not lose any light. The average amount of light loss is 0.014. The beam footprint on M1 and the camera lens aperture for the worst system is shown in figure 4.

The most likely errors to cause loss of light are errors in tilts to the flat mirrors. If the errors to M2-M7 are increased from 1 milliradian to 2 milliradian, only roughly 20% of the systems have no loss of light, and the average loss goes up to approximately 0.2. With two milliradian tilts, there is a possibility of severe darkening of edges or corners, as shown in Figure 5.

If we increase the errors to three milliradian, some systems get loss of field of view and darkening of large parts of the image, as can be seen in Figure 6.

The proton beam window system behaves very similarly to the target wheel system. With the errors specified in Section 4, 57 out of 100 systems showed no loss of light. The worst case showed some loss along a single edge of the image. With the tilt errors increased to 3 milliradian for M2-M7, some systems see dramatic loss of light, and are not able to see the entire beam window.

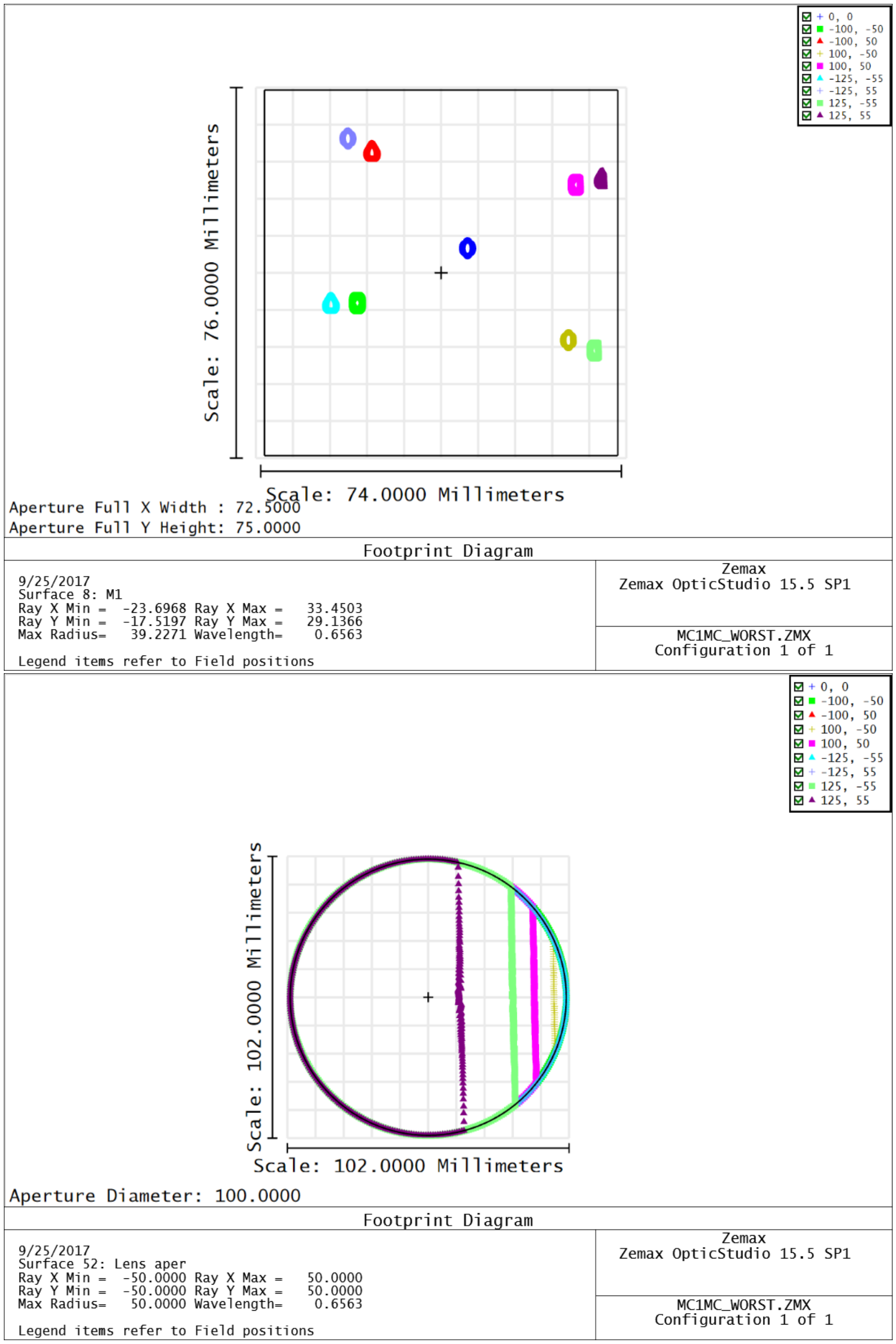

Figure 4: Beam footprint on M1 (left) and lens aperture (right). Light loss is 0.15.

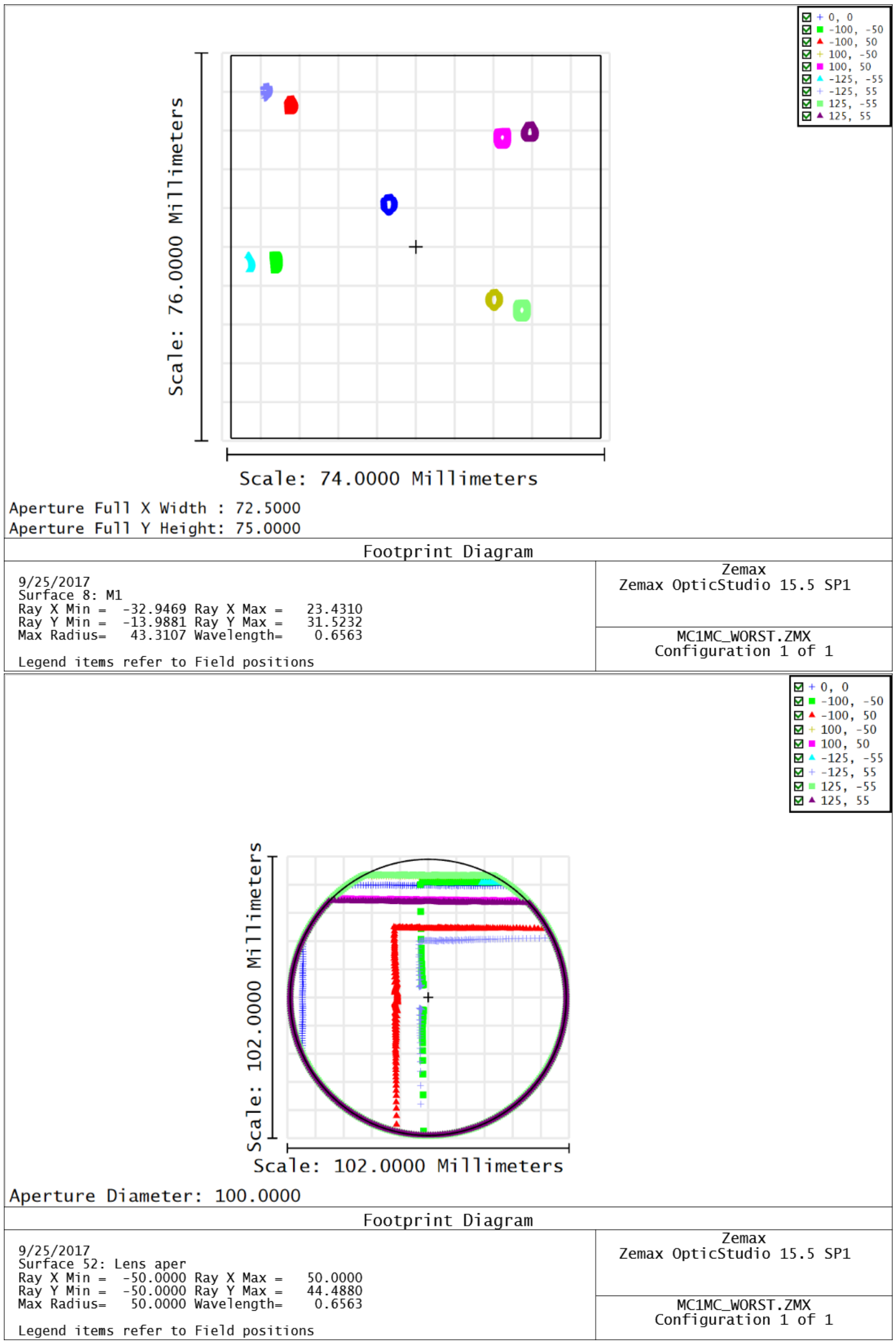

Figure 5: Beam footprint on M1 and the lens aperture, showing loss of light along two edges This system is monte carlo generated with up to 2 milliradian errors on tilt for M2-M7.

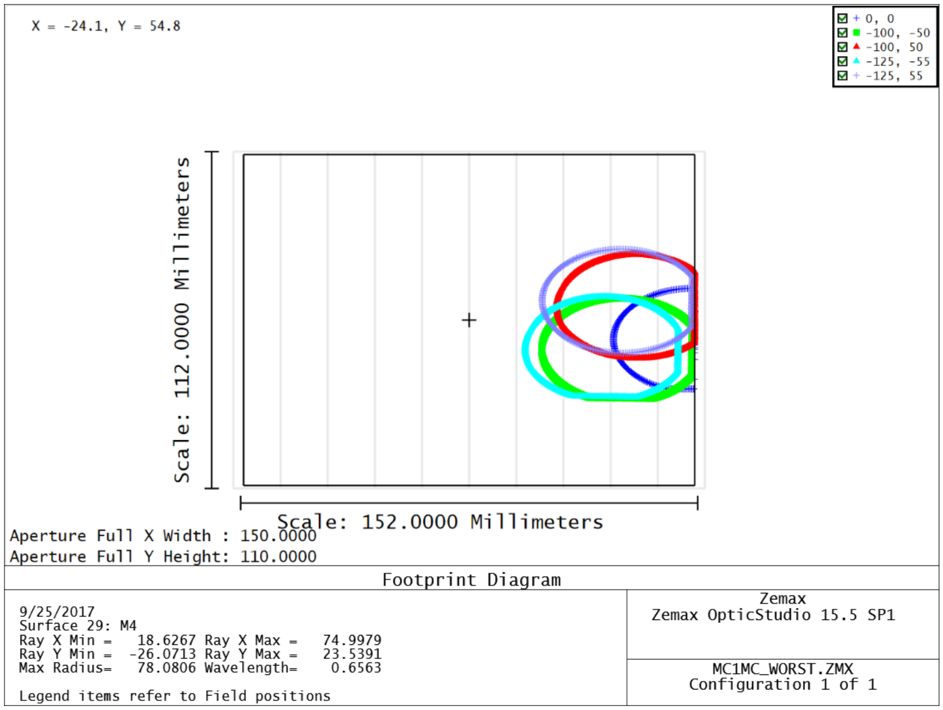

Figure 6: Beam footprint on M4, showing loss of light across the region of interest, as well as loss of field of view. This system is monte carlo generated with up to 3 milliradian errors on tilt for M2-M7.

6 Thermal deformation of M1

The thermal deformation of M1 on various mounts have been calculated in [4]. In order to study the optical effects of the thermal deformations, the deformations in the worst case heat load for the short aluminium mount have been used. The nodes in Table 17 in [4] have been transformed into a plane that is parallel to the plane where the surface is defined in Zemax, a plane where the four corners of the mirror are in $z = 0$.

Plot 7 shows the displacement along the z-axis as a function of x and y. The plots do not show a significant change in tilt of the mirror about the local x or y axis. The plots show that the mirror is slightly shifted upwards (less than 0.05mm). The surface curvature has changed, the z-position in the center of the mirror has increased by approximately 0.002mm more than the corners. This is approximately the same effect as changing the y-radius of M1 on the target wheel system from 1150 to 1115, changing the magnification of the image in one direction by a factor 0.98.

Plots 8 show that the biggest displacements occur along the surface plane.

The mirror will be heated to relevant temperatures in the lab, and the effect of the deformation will be studied.

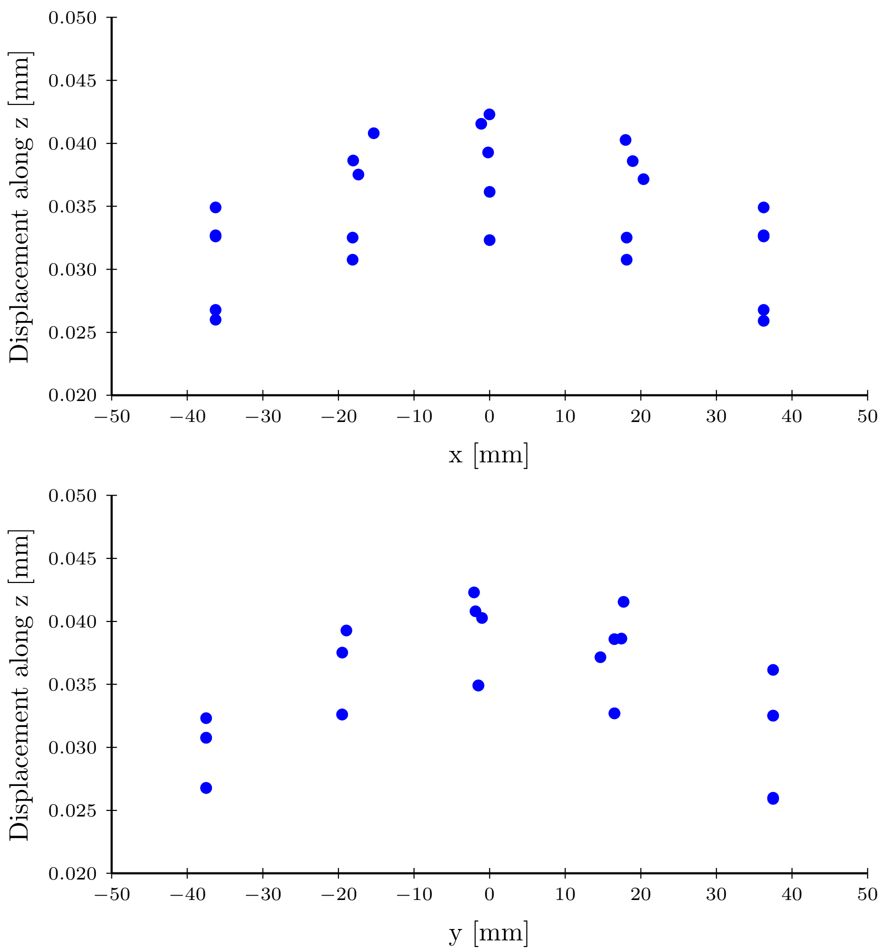

Figure 7: Z displacement vs x and y position in the mirror. Some of the points overlap.

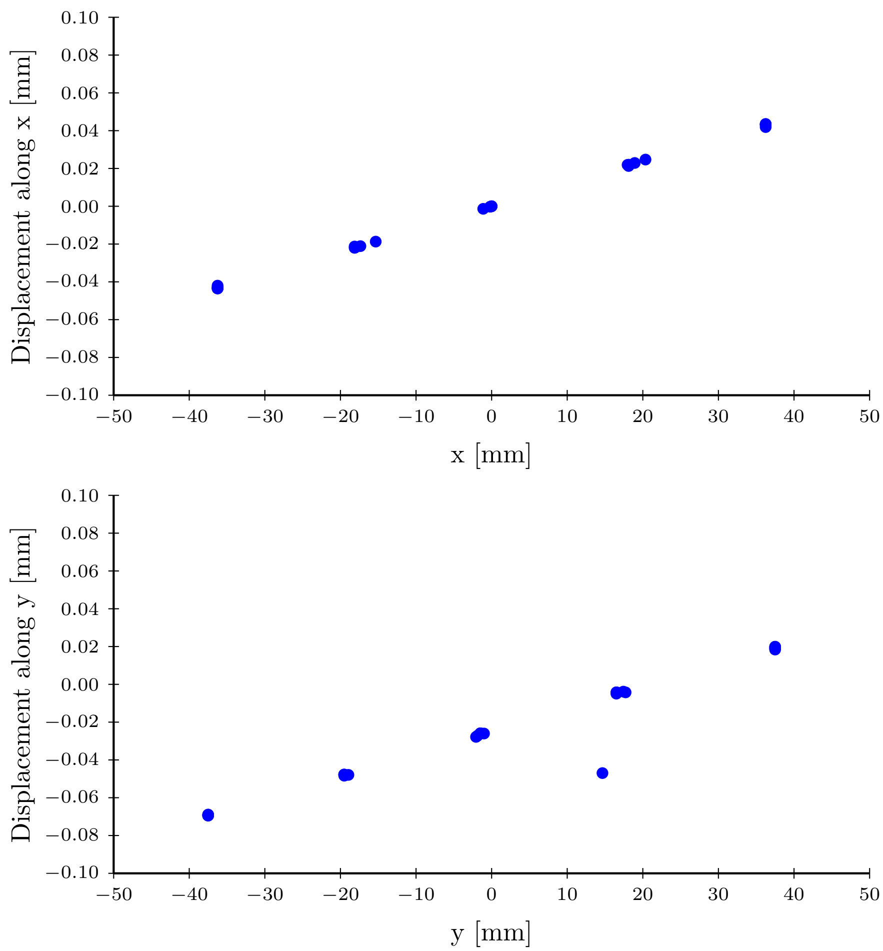

Figure 8: X displacement vs x position and y-displacement vs y-position.

7 Summary

The tolerance limits to the PBIP mirror interfaces are summarized in the table below. These errors are with respect to the PBIP itself.

	Translations			Rotations		
	X	Y	Z	X	Y	Z
M1	1 mm	1 mm	1 mm	0.3°	0.3°	0.3°
M2-M7	5 mm	5 mm	5 mm	0.3°	0.3°	0.3°

The tolerance limits when moving the PBIP from the mock-up to the target monolith listed in the table below.

	Translations			Rotations		
	X	Y	Z	X	Y	Z
PBIP	5 mm	2 mm	2 mm	0.3°	0.3°	0.3°

The tolerances for movement after the plug has been installed are in the table below. The errors are with respect to the target coordinate system.

	Translations			Rotations		
	X	Y	Z	X	Y	Z
M1	1.5 mm	1.5 mm	1.5 mm	0.3°	0.5°	0.5°
M2	1 mm	1 mm	1 mm	0.06°	0.06°	0.06°
M3	1 mm	1 mm	1 mm	0.06°	0.06°	0.06°
M4	2 mm	2 mm	2 mm	0.06°	0.06°	0.06°
M5	2 mm	2 mm	2 mm	0.06°	0.06°	0.06°
M6	2 mm	2 mm	2 mm	0.06°	0.06°	0.06°
M7	2 mm	2 mm	2 mm	0.06°	0.06°	0.06°

The tolerances in M1 comes from three sources:

	Translations			Rotations		
	X	Y	Z	X	Y	Z
Thermal deformation to the interface	1 mm	1 mm	1 mm	0.3°	0.3°	0.3°
Thermal deformation of mirror with mount	0.1 mm	0.1 mm	0.1 mm	0.1°	0.1°	0.1°
Initial misalignment	0.4 mm	0.4 mm	0.4 mm	0.1°	0.1°	0.1°

The clear aperture between M1 to M2 should be no smaller than 80 mm × 75 mm. The clear aperture between the following mirrors should be no smaller than 100 mm × 100 mm.

8 References

[1] Target optical systems, ESS-0149764
[2] Thermal deformation of the PBIP, ESS-0052276
[3] Bendamount, ESS-XXXXX
[4] Thermal heat load analysis of first mirror, ESS-0149765