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Target Optical System Design Document

	Name	Role/Title
Owner	Håvard Gjersdal	
Reviewers	Erik Adli Cyrille Thomas	
Approver		

Contents

1 Scope

This document describes the optical systems that collect light from the proton beam window and the rim of the target wheel, imaging it onto cameras in the A2T access area. The parameters of these optical systems, as well as their simulated performance are detailed.

A prototype of the target wheel optical system that has been built in Oslo is described. The performance of the prototype is summarized.

2 Introduction

The design of the optical systems for the target proton beam imaging systems is presented here. Two optical systems will be installed, one looking at the proton beam window (PBW), and one looking at the beam entrance window on the target wheel (TW). Light will be generated when the proton beam interacts with scintillating material coating the PBW and the rim of the target wheel. The optical systems described here will transport this light and image it onto cameras in the A2T access area.

3 General concept

Figure 1 shows the two optical paths for the optical systems. Light is transported up through the proton beam instrumentation plug (PBIP), through viewports in the vacuum vessel, through apertures in the shielding wall, and to the camera. The optical path through the PBIP is shown in figure 2.

The two optical systems are similar in design and performance. Each system consists of 7 mirrors, designated M1-M7, where M1 is closest to the light source (the PBW or TW scintillating coating). M1, M2, M3, and M4 are mounted on the PBIP. The first mirror in each path, M1, is curved. The curved mirrors create a demagnified virtual image of the region of interest. The curved mirror demagnifies the object, and allows the full region of interest to be seen through the PBIP aperture. The aberrations caused by the curved mirrors are sufficiently small to not affect the requirement of 1mm resolution, so the aberrations are not corrected for with optics. The main aberration is distortion, which will be corrected in software.

To maintain the shielding integrity, chicanes are needed in the middle of the PBIP (M2 and M3) and after the shield wall (M6 and M7). The mirrors M4 and M5 are needed for steering the beam through the viewports and the aperture in the shield wall, and towards the cameras.

Imaging onto the camera sensor is done by a camera lens. The aperture in the shield wall is 100mm × 100 mm, if the lens aperture is much larger than this it will cause vignetting. The systems have been designed, and tolerances have been calculated, for a lens aperture of 100mm. The exact focal length of the lens that will be installed has not yet been determined, and to some extend it depends on the sensor and pixels size of the camera, as discussed in [1]. A 600mm lens, possibly with a 1.4x teleconverter, is a likely candidate.

The systems have been designed and tested with simulations using Zemax OpticStudio. A prototype for the TW system has been built, using a 600mm f/4 Nikkor lens for imaging. The lens is operated at f/5.6.

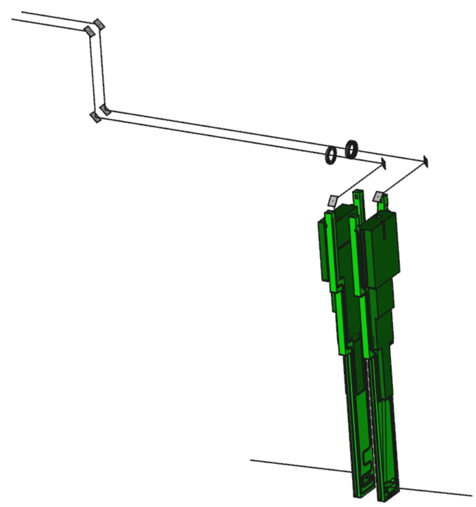

Figure 1: The optical paths from the TW/PBE to the cameras. The PBIP and the vacuum windows are included in the model.

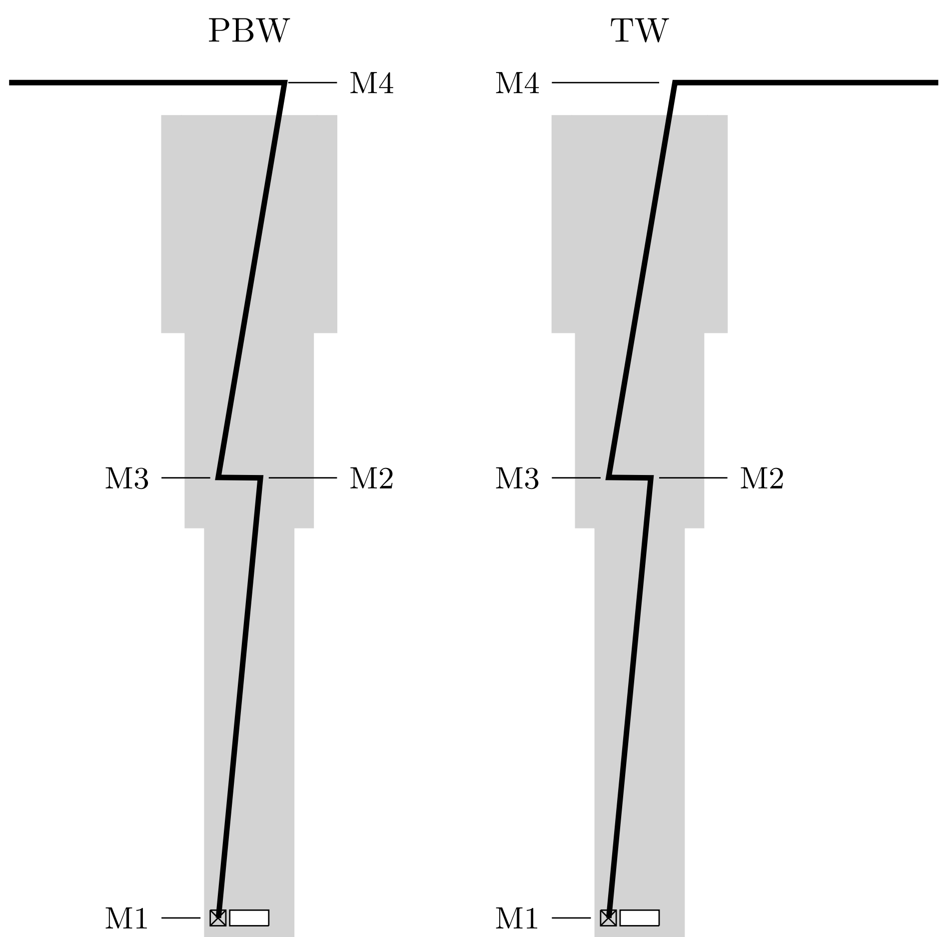

Figure 2: The optical path through the PBIP for the target wheel and the proton beam window systems as seen from the object.

4 Requirements

The requirements for the optical systems are:

- Provide a 250mm × 110mm field of view, that covers the beam window, along with fiducials around it.
- Provide a resolution better than 1mm in object space, across the beam window. A resolution better than 1mm means the system should be able to resolve parallel lines with a 1mm spacing in both the horizontal and vertical direction.
- The system needs to transport sufficient light for the electronics system to qualify the beam on target properties for every pulse. The amount of light collected should be maximized, without breaking other requirements.
- The radiation shielding must not be compromised, to ensure that the radiation level is kept below the defined levels in access areas in the connection cell and A2T access area. This limits the maximum aperture in the PBIP and through the shield wall to 100mm × 100mm, and necessitate chicanes in the PBIP and behind the shield wall.

5 Parameters of the optical system

The optical design has been created with the software Zemax OpticStudio. The mirrors and rays have been integrated into CAD models of the target area and connection cell. The Zemax OpticStudio design files are attached to this document, as is the prescription data that describes the key geometrical and optical parameters of the system.

Some key parameters of the optical systems are described below. The positions are for the center of the mirrors in the PBIP coordinate system. All units are millimeters. A more complete specification of the system, including the rotations of all the elements and position and dimensions of the apertures included, are listed in the attached prescription data.

Tolerances for the alignment parameters are listed in [2].

5.1 Mirror positions and dimensions for the TW system

Mirror	X	Y	Z	Dimensions
M1	200	-158	0	72.5 × 75.0
M2	222	57	2255	120 × 90
M3	222	-160	2257	120 × 90
M4	262	181	4280	150 × 110
M5	262	1526	4280	110 × 150
M6	-4920	1526	4280	150 × 110
M7	-4920	1526	5580	150 × 110

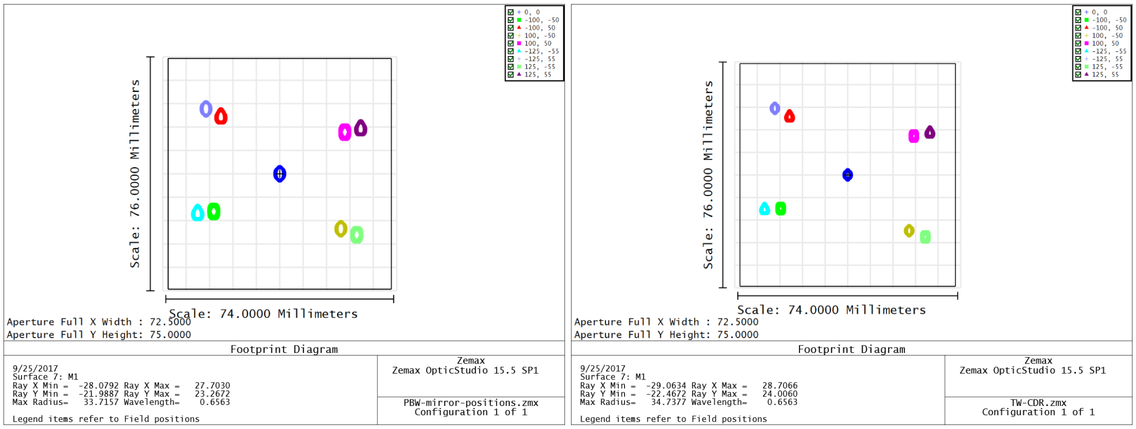

Figure 3: Beam footprint on M1. PBW side to the left, target wheel on the right. The different colors represent light coming from different points in the object. The points are the center and corners of the beam window, as well as the corners of the area for fiducials. The curvatures of the mirrors have been adjusted so that the beam footprint is of approximately the same size. The beam footprint does not fill the entire mirror, giving us a buffer that can absorb errors in alignment from installation and thermomechanical stress.

5.2 Mirror positions and dimensions for the PBW system

Mirror	X	Y	Z	Dimensions
M1	-200	158	0	72.5×75.0
M2	-222	-57	2255	120×90
M3	-222	160	2257	120×90
M4	-262	-181	4280	150×110
M5	-262	1251	4280	110×150
M6	-4920	1251	4280	150×110
M7	-4920	1251	5580	150×110

5.3 Curved mirrors

The curved mirrors are tilted biconic mirrors. The cross section through the local x and y axes form conic cross sections with different radii (R_x and R_y) and conic constants (k_x and k_y). The surface of the mirror follows

$$z(x, y) = \frac{\frac{x^2}{R_x} + \frac{y^2}{R_y}}{1 + (1 + k_x)\frac{x^2}{R_x^2} - (1 + k_y)\frac{y^2}{R_y^2}}. \tag{1}$$

For the PBW system, the radii are $R_y = 1533$ and $R_x = 700$. For the TW system, $R_y = 1150$ and $R_x = 550$. The conic constants are zero. The curvatures are adjusted so that the beam footprint in the first mirror is approximately the same size, as shown in Figure 3.

The errors in the mirror radius from manufacturing will be less than 0.5% of the specified radius, meaning that changes to the size of the virtual image due to mirror production errors will not be significant.

5.4 Vacuum window

The vacuum windows should be fused silica, $\lambda/4$ or better. The radius of the clear aperture should be no smaller than 50mm. A window that is able to withstand a 2 bar pressure difference has been identified.

5.5 Clear aperture

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. The mirrors in the PBIP chicanes will be slightly smaller than the clear aperture, to allow for some flexibility for alignment. The mirrors from M4 to M7 will be bigger than the minimum clear aperture, as there will be more space around the mirrors for adjusting alignment letting us use the entire aperture. The clear aperture in shield wall should be no smaller than than 100mm × 100mm, and the clear aperture in vacuum window should have a radius no smaller than 50mm.

5.6 Mirror materials

The baseline presented at the PDR was to use uncoated aluminium mirrors inside the target atmosphere. There is a risk that the target atmosphere will be corrosive for aluminium, so protective mirror coatings are now being considered. This is discussed in [3].

6 Simulated performance

The full field of view of the system is approximately 300 mm × 200 mm in object space, significantly larger than the 250 mm× 110 mm required.

The entrance pupil of the system is not perfectly circular, but the numerical aperture is approximately equivalent to 0.001.

Zemax models of modern telephoto lenses are not available. The resolution of the optical systems from the simulation is instead estimated by studying the virtual image behind the last mirror before the camera with a 100mm circular aperture at the camera position. Figure 4 shows the MTF, a measure of contrast, as a function of sinusoidal cycles per mm in image space. The magnification of virtual image in the two systems are both 0.3, so roughly three lines per mm in image space must be visible in order to see one line pair per mm in object space. This resolution is achieved in simulations, and confirmed in the prototype with a 600mm f/4 lens.

The full field of view in simulation is larger than the region of interest. The sizes of the mirrors are larger than the beam footprint in all mirrors.

The shape of the first mirrors does lead to deformations, as shown in the simulated image in Figure 5.

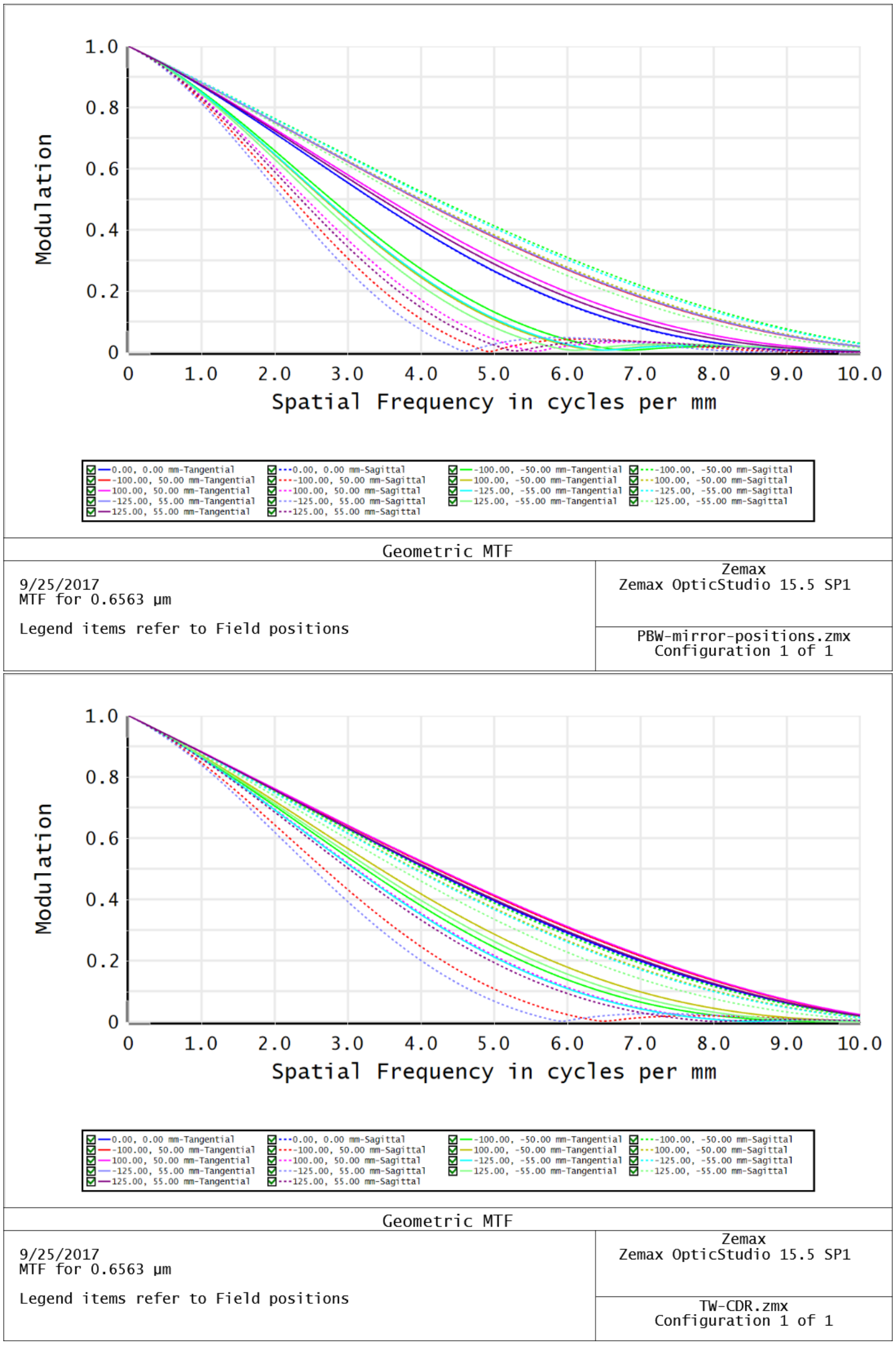

Figure 4: MTF vs sinusoidal cycles per mm in image space for the PBW system (top) and the TW system (bottom). Both systems have a magnification of 0.3, and a simulated resolution better than one cycle per mm in object space.

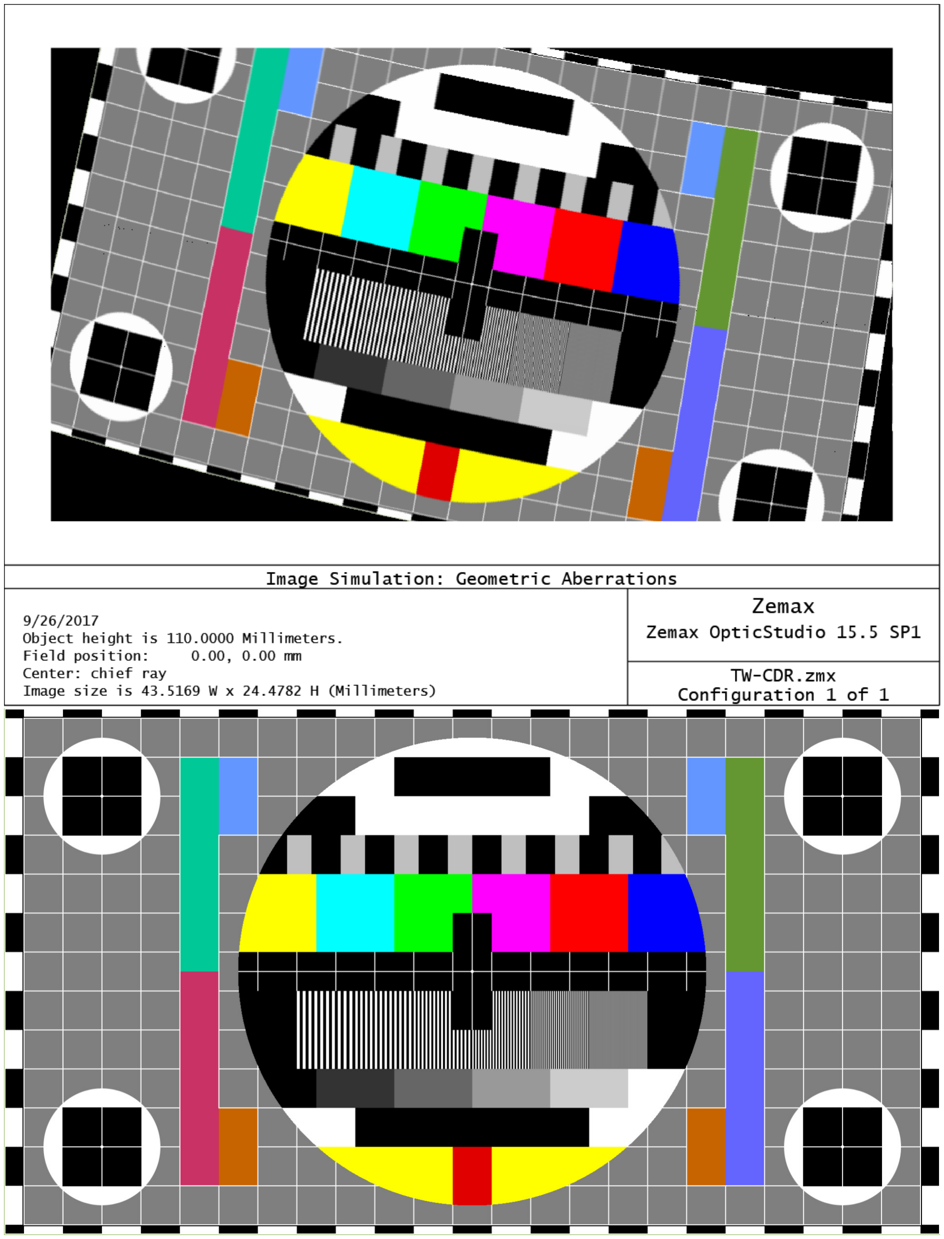

Figure 5: The top image is the simulated image through the target wheel imaging system. The image is the virtual image as seen on M7. The original test pattern is shown below. The simulated image shows the expected deformations of the image, not the full field of view.

7 Differences to system based on curved mirrors

At the proton beam imaging system PDR, an optical system based on several curved mirrors was presented. The optical system has been simplified, due to concerns about alignment of the all reflective system. The simplified system provides similar performance, without the concern for loss of image quality due to misalignment.

A system with several curved mirrors is able to collect more light, but controlling optical aberrations becomes harder as the amount of light increases. With several curved mirrors, we were not able to get a resolution near 1mm unless we reduced the numerical aperture to approximately 0.001. Even with a numerical aperture of 0.001, the resolution of the system was expected to drop below 1 mm with realistic errors on alignment.

8 Prototype

A prototype of the target wheel optical system has been made at the University of Oslo. The prototype is shown in figure 6. The relative positions of the object, M1, M2, M3 and M4 are within 10 mm of the Zemax model. The positions of M5-M7, as well as the camera, are not the same as for the final system, as can be seen in the figure. This is due to space constraints in the lab. The total light path distance in the prototype system matches that of the final system model to within 500mm.

The size and curvature of M1 has been updated after commissioning of the prototype in order to increase the tolerances for tilts in the PBIP and M1. The prototype M1 is a biconic mirror with , $R_y = 1150$, $k_y = -12.5$, and $R_x = 600$. The mirror is 72.5mm × 65mm, and is mounted on a Manfrotto MHXPRO-BHQ6 ball head.

M2-M7 100mm × 100mm $\lambda/4$ mirrors are from Edmund Optics. They are mounted on kinematic platform mounts from Thorlabs, KM200B/M. To reduce the chance of vignetting with the smaller mirrors, M7 is as far away from the camera as possible, and close to orthogonal to the optical axis.

An image of a test pattern as seen through the optical system is shown in Figure 7. The figure shows the deformation of the system. It shows that 1mm resolution is achieved across the beam entrance window. The full region of interest is visible, with an margin around it. All the results agree well with simulations.

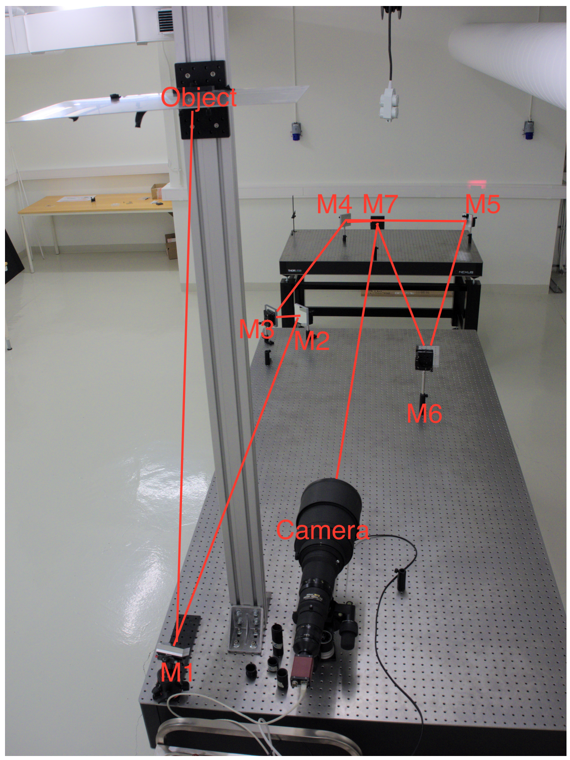

Figure 6: The prototype of the target wheel system.

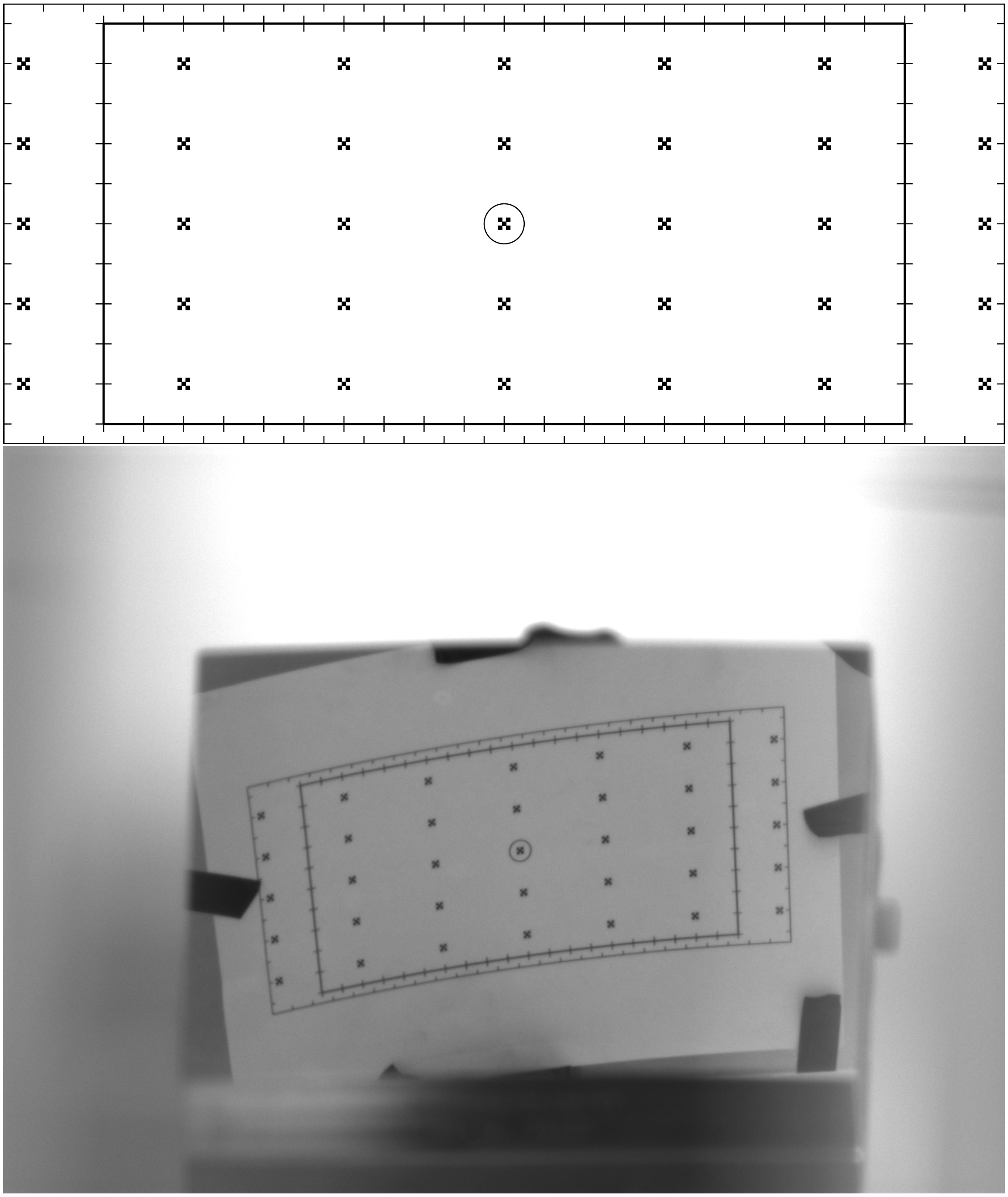

Figure 7: Performance of the prototype. The top picture shows a test pattern, where the outer box is the 250 mm × 110 mm region of interest that includes fiducials. The inner box is the 200mm × 100mm beam entrance window. The chess patterns across the region of interest are 3 mm × 3 mm, made up of 1 mm × 1 mm squares. The second image is a photo of the test pattern through the prototype. The outline of M1 is visible, indicating that the full field of view is larger than the region of interest. The chess pattern can be resolved across the region of interest.

9 Illumination system

An illumination system is needed to see the retroreflective fiducials on the objects. Placing a small obscuration directly in front of the camera lens has very little impact on the system performance, so an illumination system can be made by simply placing a collimated light source in front of the camera.

The illumination system used in the prototype is shown in Figure 8.

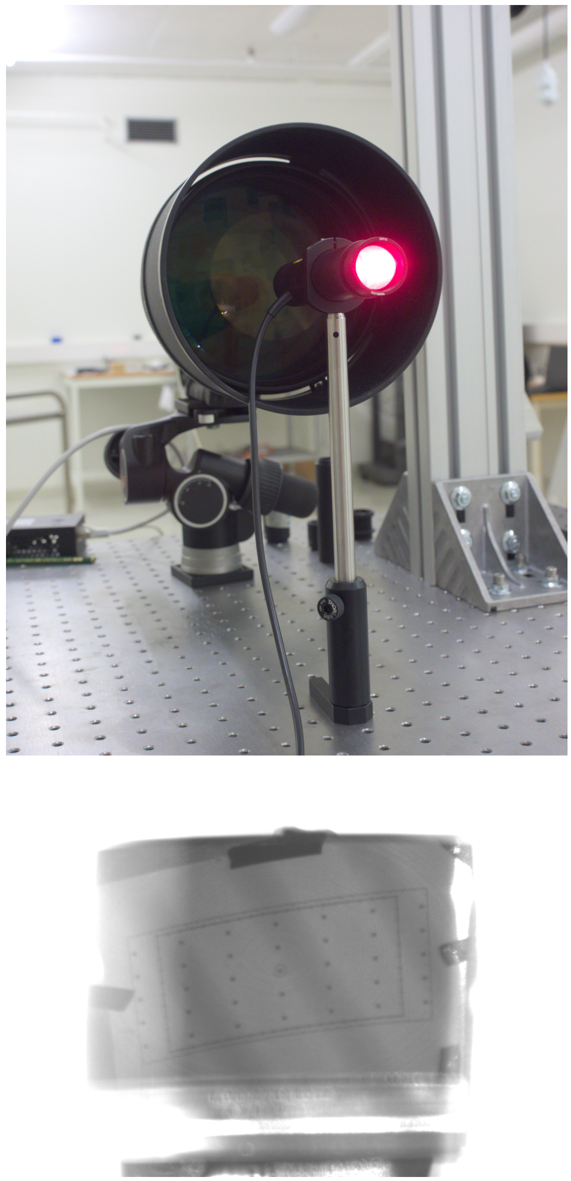

Figure 8: The top picture shows the ihe illumination system for the prototype that consists of a 1in 660nm LED (Thorlabs M660L4) collimated by a f=300mm plano-convex lens. The bottom image shows the illuminated test-pattern as seen through the optical path. The diagonal lines are due to the LED arrays on the source.

10 Procurement strategy

We have been in contact with Kugler GmbH for a quote on the full set of mirrors.

The price for the small flat mirrors, M2 and M3, will be 880€ per piece. The larger mirrors, M4-M7, will cost 980€ per piece. Lead time for the flat mirrors will be approximately 4 months.

The biconic mirrors will cost 2550€, and have a lead time of 6-7 months.

The curved mirrors will be ordered when the preferred coating has been determined, and we have confirmation that the tolerance limits for the tilt of the plug and for M1 can be met. A discussion of mirror coating can be found in [3]

11 Summary

Two optical paths have been designed, one for imaging the proton beam window and the other for imaging the target wheel. Both systems have a field of view larger than 250 mm × 110 mm in object space, with a resolution better than one mm. The numerical aperture of the two systems are approximately 0.001.

A prototype of the target wheel system has been made at the University of Oslo. The performance of the prototype agrees well with simulation.

12 References

[1] Electronics/software functionality document, ESS-0150748
[2] Alignment tolerances, ESS-0149766
[3] Plan for the protection of Target Imaging Systems Mirrors against Nitric Acid, ESS-01150766