X-shooter Near-IR Spectrograph Arm: Design and Manufacturing Methods

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ABSTRACT

X-shooter, the first 2nd generation VLT instrument, is a new high-efficiency echelle spectrograph. X-shooter operates at the Cassegrain focus and covers an exceptionally wide spectral range from 300 to 2500 nm in a single exposure, with an intermediate spectral resolving power R~5000. The instrument consists of a central structure and three prism cross-dispersed echelle spectrographs optimized for the UV-blue, visible and near-IR wavelength ranges. The design of the near-IR arm of the X-shooter instrument employs advanced design methods and manufacturing techniques. Integrated system design is done at cryogenic working temperatures, aiming for an almost alignment-free integration. ASTRON Extreme Light Weighting is used for high stiffness at low mass. Bare aluminium is post-polished to optical quality mirrors, preserving high shape accuracy at cryogenic conditions. Cryogenic optical mounts compensate for CTE differences of various materials, while ensuring high thermal contact. This paper addresses the general design and the application of these specialized techniques.

Keywords: X-shooter, infrared, cryogenic, design at working temperature, ASTRON extreme light-weighting, post-polish aluminium mirror, cryogenic optical mount, spectrograph

1. INTRODUCTION

X-shooter is a single target, wide-band medium resolution spectrograph for the VLT. The wavelength range is 0.3 to 2.5 μm i.e. from the UV to the IR K-band. X-shooter is a Cassegrain focus instrument and has only one observing mode and a fixed spectral format [Ref. 1].

The instrument consists of a central structure (the Backbone) onto which three spectrographs are mounted that cover the UV-Blue, VISible and Near InfraRed (NIR) spectral ranges [Ref. 2]. The Backbone contains the calibration system, Acquisition and Guiding camera, Atmospheric Dispersion Correctors and dichroics to split the light from the telescope in three wavelength bands. Active mirrors compensate for flexure inside the backbone and keep the three slits aligned at the same position on the sky.

The focus of this paper is on the NIR Spectrograph, its advanced design methods and the manufacturing techniques involved. The NIR Spectrograph is cooled with liquid nitrogen bath cryostat as closed cycle coolers may cause unwanted vibrations. The instrument operates at 105 Kelvin, while the detector is cooled to 82 Kelvin. As X-shooter is located at the Cassegrain focus it suffers from a changing direction of the gravity vector. By using light-weighted mirrors and a light-weighted mechanical structure the stiffness to weight ratio is optimized, which allows the instrument to be build just inside the VLT mass limit. The suspension of the NIR Cold Optics box inside the cryostat is done with three titanium rods, combining strength (earthquakes) and stiffness with a low heat load. The cryostat diameter is 1200 mm, its mass is 550 kg.

The optical design of the X-shooter NIR Spectrograph consists of a warm optics box, a cryostat entrance window and some folding mirrors to keep the cryostat as small as possible. From the slit the light passes the collimator and enters the dispersion box, consisting of an echelle grating in near-Littrow configuration for the main dispersion and three prisms in double pass for the cross dispersion. The light passes the collimator again, enters the camera and reaches the detector [Ref. 3]. The cold optics box is shown in figures 1 and 2.

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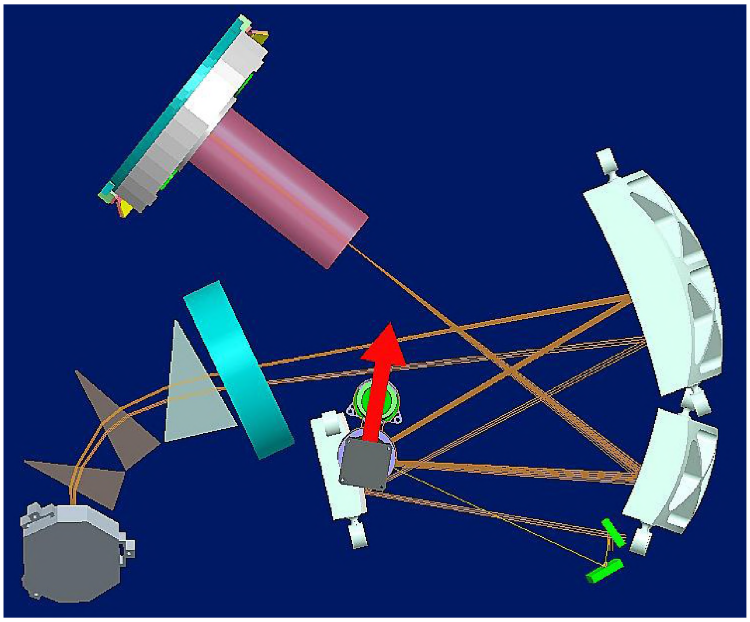

Fig. 1. The optical design of the X-shooter NIR Spectrograph. The Cassegrain focus is indicated by the arrow in the center and is situated above the plane of the paper, while the warm optics and the cryostat entrance window are shown behind this arrow (also situated above the paper). The slit is located in the lower right. The light beam passes two collimator mirrors (upper right) and enters the dispersion box on the left. The dispersion box consists of three prisms and an echelle grating. The light passes the collimator again, enters the camera and hits the detector in the upper left.

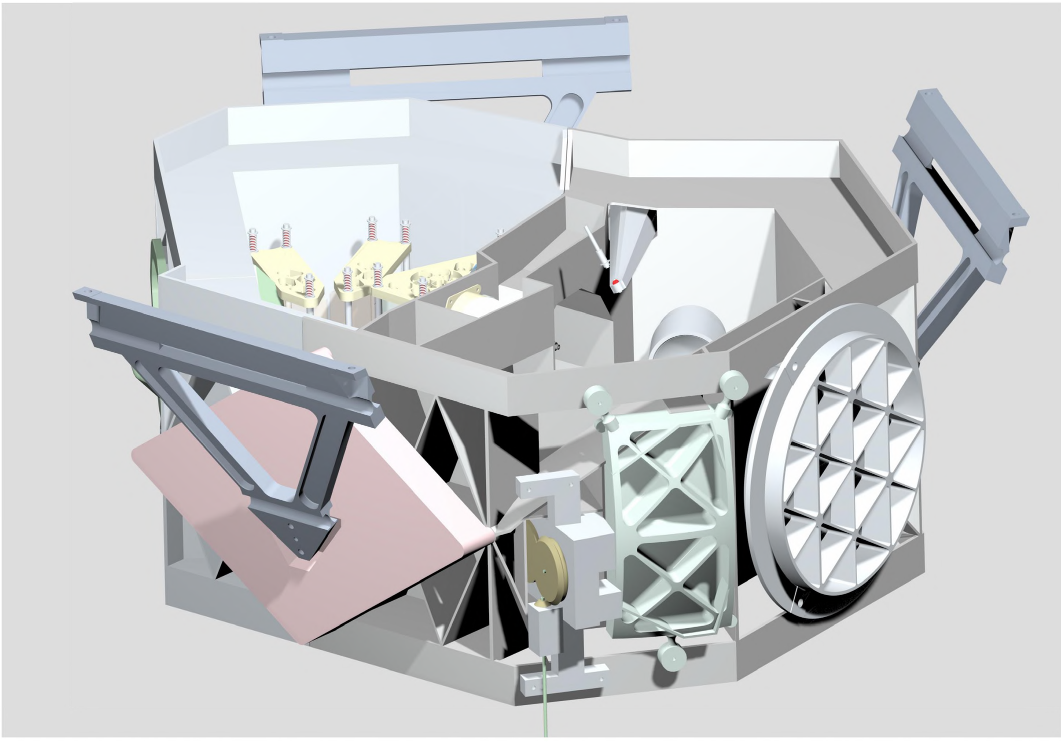

Fig. 2. The NIR cold optics box, top cover removed, with its three point rod suspension (triangles). The main collimator mirror is located on the right and is open back light-weighted. The extreme light-weighted balance arm is located in the lower left (diamond shape), while the tops of the prism mounts are visible in the upper left area. The slit unit is located in the lower middle and the camera and detector in the upper right. The warm optics is not shown in this figure.

2. DESIGN AT CRYOGENIC WORKING TEMPERATURE

In a monolithic design all components, including the mechanical structure and the optical mirrors, are made of the same aluminium material, in this case Al.6061-T6. Manufacture, assembly and alignment of the opto-mechanics is done at room temperature. Due to the Coefficient of Thermal Expansion (CTE) of aluminium the whole structure shrinks by 3.4 mm when the instrument is cooled down to cryogenic working temperatures. Because all these components are made of the same material, the radius of the mirrors shrinks by the same percentage. The net result is that the temperature change does not have any optical effects.

Of course the monolithic design philosophy does not hold when transmission optics of a different material has to be used in the design. For gratings this happens, even if the material used is aluminium. There will always be a relative shrink or expansion of the optical element with respect to its mounting surfaces. In figure 3, the isostatic point is shown for various optical elements with a CTE that is different from the mechanical structure. The mechanical structure must contain some sort of spring mechanism in order to ensure proper positioning during cool down and warm up of the system.

If transmission optics is used in a cryogenic optical design, it is essential to work with both a cold and a warm design. The cold design is at cryogenic operation temperatures to predict instrument performance and the warm design is at room temperature for manufacture, integration, alignment and test. The two designs are necessary, because alignment of optical elements in a cryogenic environment is virtually impossible, making the pursuit of an alignment-free integration essential for a short verification period and timely delivery of the system.

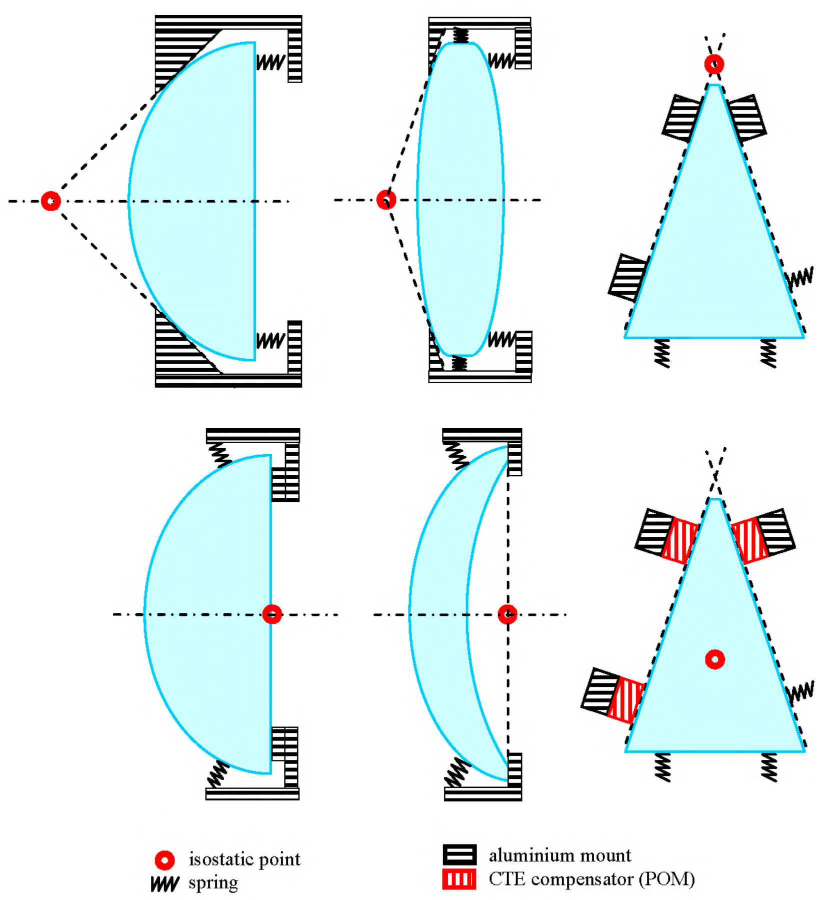

Fig. 3. A monolithic design is impossible if transmission optics materials are used with a CTE that is different from the CTE of the mechanical mount. The circle indicates the location of the isostatic point for various shapes and mounting methods of lenses and prisms. The isostatic point can be moved to a more favorable location by using a certain thickness of CTE-compensating material such as POM (Chapter 3).

For one-dimensional optical designs, such as a set of lenses for a camera, ZEMAX is perfectly capable of interchanging between the cold and warm mode, as long as the isostatic point or reference position for each optical element is defined correctly. For a rather difficult three dimensional structure, like the X-shooter NIR cold optics box, this approach is too error prone as the isostatic point is hardly ever located on the optical surface and sometimes not even on the optical axis (prisms and off axis lenses). ZEMAX is not fit to perform the 3D calculations needed. A mechanical design program like Pro-Engineer is capable to interchange between the cold and warm design at the push of a button.

On top of the argument above it sometimes is too soon to fix the location of the isostatic point when designing the optics in ZEMAX. This is because the mounting method and thus the location of the isostatic point is merely a mechanical choice, depending on available space around the optical components and on the oversize of the optical elements (the area outside the optical footprint).

For the X-shooter NIR Spectrograph it was chosen to design the complete instrument at working temperatures. This is the best way to ensure a working instrument in the end. All elements are virtually warmed-up to room temperature before making the drawings for manufacture, see the flowchart in figure 4.

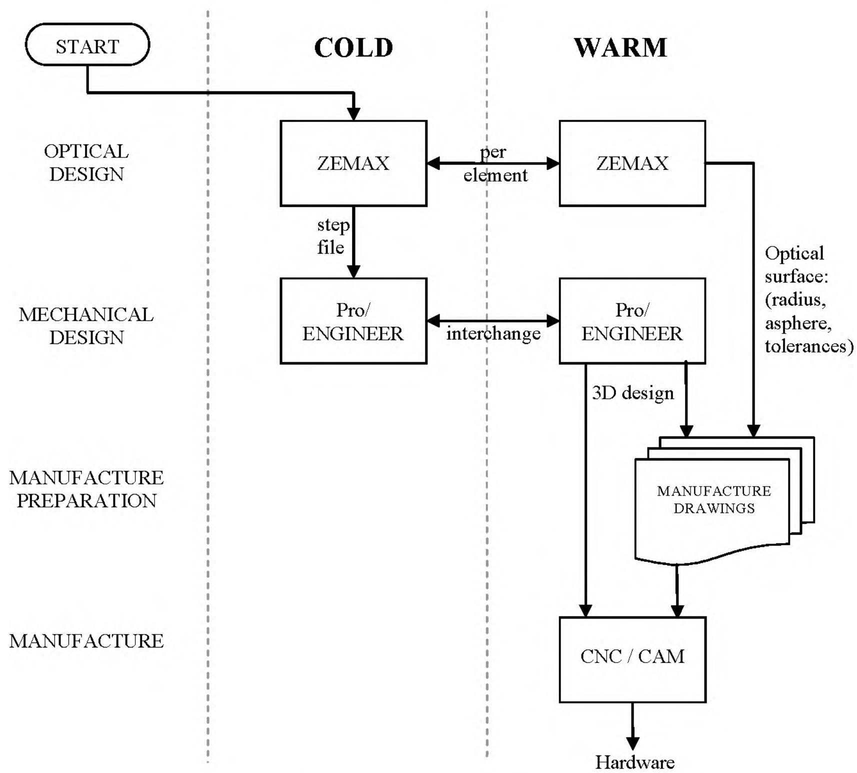

Fig. 4. Flow diagram for the design and manufacture of a cryogenic IR device. The design starts with an optical model at working temperatures. A mechanical model is created to mount the optical components and to match the stability requirements of the optical model. Both models are warmed-up in order to generate the drawings for manufacture.

A warm optical model is created for Assembly, Integration and Test (AIT) of the instrument, using 3D data from the mechanical design. This warm optical model determines the set point for the alignment, using the results of the acceptance tests of the (optical) elements. If the instrument does not pass the cold acceptance test, the test data is used to update the cold optical model and a new warm alignment set point is determined, see the flowchart in figure 5.

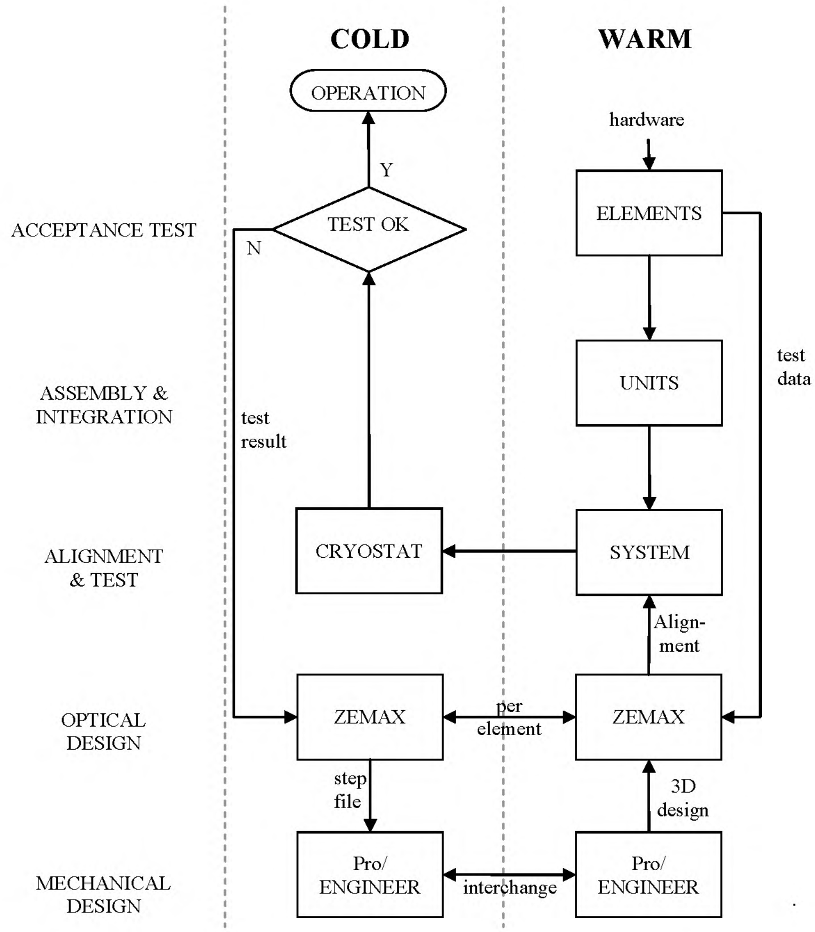

Fig. 5. Flow diagram for the Assembly, Integration and Verification of a cryogenic IR device. A warm optical model is created using data from the warm mechanical model. In a warm acceptance test the (optical) elements are measured and the test data is entered into the warm optical model, which is used to determine the set point for the warm alignment. If the cold acceptance test is not passed, the test data is used to update the cold optical model and a new alignment set point is determined.

3. CRYOGENIC OPTICAL MOUNTS

Cryogenic optical mounts have contradicting mechanical requirements. The position of all optical elements must be accurate and stable at cryogenic conditions, also when different materials are used, like lenses in the camera or prisms. However, sufficient freedom of movement must be allowed to compensate for differential shrink of these materials during cool down & warm up. On top of that cryogenic optical mounts require good thermal contact between the mounting structure and the optical elements in order to limit cool-down and warm-up times. Finally the allowed forces on the optical elements are limited, because they can cause stress and birefringence in the optical material.

Good thermal contact is most challenging. A single large contact area between prism and mount would be sufficient for good thermal contact, but this would lead to unacceptable stress and birefringence in the prism due to CTE differences. Among the other options considered is radiation cooling. Radiation cooling is very efficient at higher temperatures due to the $\sim T^4$ dependency. In practice however, a thin layer of black paint, applied to non-optical surfaces of the optical element, causes sufficient high stress levels to peel chirps of paint and optical material from the optical element. The use of a thermally conductive glue to attach thermally conductive leads to the optical element has similar destructive effects.

Considering the requirements above a solution has been chosen that uses multiple small ($\sim$1 cm^2) contact pads of two types. Fixed contact pads for mechanical contact provide position accuracy and stability. Flexible contact pads provide thermal contact and distribute forces over a larger area. This approach has been used for both the cryogenic prism mounts and the cryogenic lens mounts. The design of the prism mount is illustrated in the next paragraphs.

For the position stability, the rotation of the prism around the optical axis is critical. Three fixed pads on the bottom maintain the prism rotation. A Kapton layer on top of these pads lowers the friction to allow the pads to slide over the prism surface during cool-down. To reduce the sliding distance, the isostatic point is moved towards the center of the prism (figure 3, bottom right). This is achieved by POM pieces of calibrated thickness on the sides of the prism (outside the footprint) to compensate for the CTE difference of the optical element and the aluminium mount. Springs apply a constant force on the other side of the prism to allow freedom of movement during temperature transitions, while maintaining contact with the fixed POM pads. On the top side of the prism a symmetrical pattern of pads is pressed down using springs to ensure stable contact with the three fixed pads on the bottom of the prism.

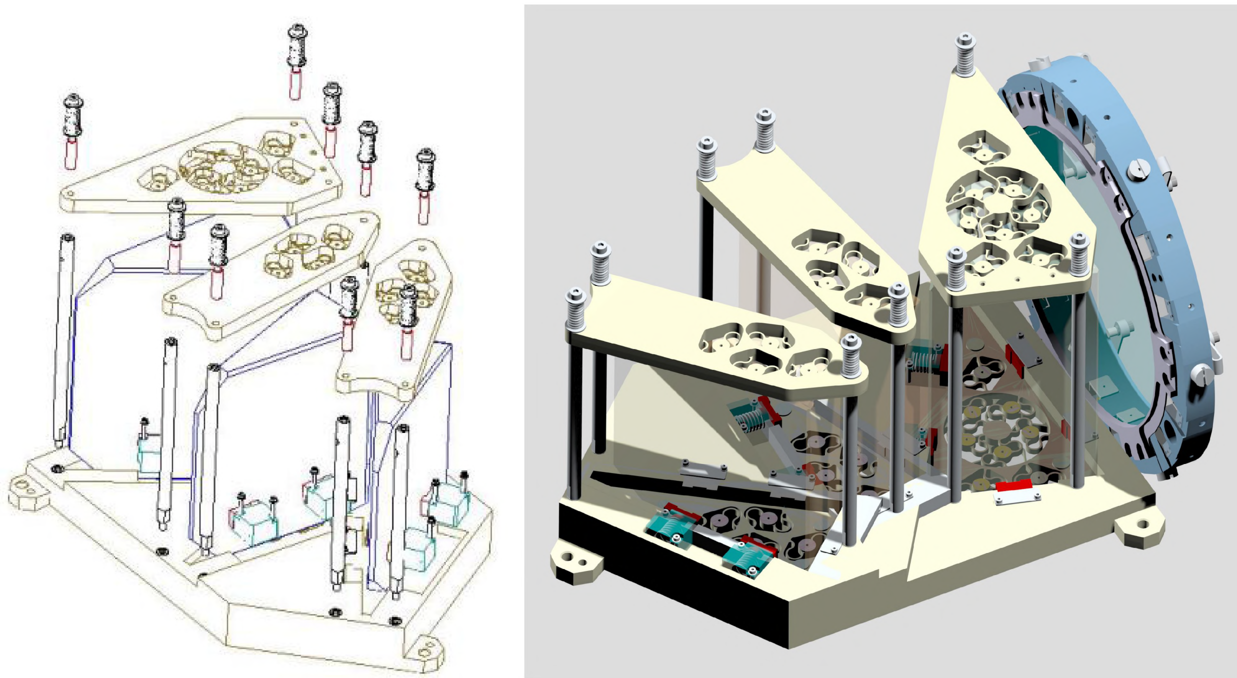

Fig. 6. Exploded view of the prism base plate with three prisms and a 3D view of the three prisms mounted on the prism base plate, together with the corrector lens.

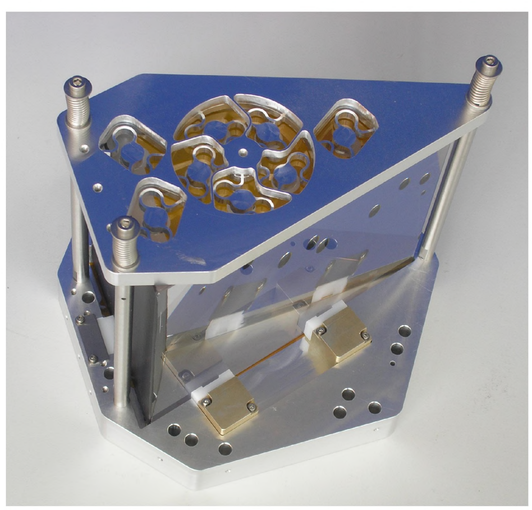

Fig. 7. Photo of the prism test mount used to test the thermal resistance between the contact pads and the prism.

Thermal contact is optimized by adding pads to the top and bottom plate. These pads are mounted on flexible springs with an indium layer for thermal contact with the prism. The usage of indium raises the friction between prism and mount. The spring applies a force perpendicular to the surface of the prism, while the pad can move sideways to allow differential shrink of the materials. The contact surface area and the spring rate of the pads have been optimized, resulting in a futuristic shape. The pads in the top mount and bottom mount are milled from a single piece to optimize the production process, see figures 6 and 7. The thermal conductivity per pad behaves roughly as ~T^2 with measured values of 50 mW/K at 273 K and 10 mW/K at 100 K.

4. ASTRON EXTREME LIGHT WEIGHTING

Due to strict optical requirements, very low global and local dynamic elastic deformation is allowed in the cold optics box during operation, resulting in a design with a high stiffness to weight ratio. A three point isostatic suspension is used in order to minimize deformation in the cold optics box by external forces. This is however less favorable for the deformations in the box due to its own weight. A four point suspension performs twice as good in that respect. In order to benefit from both aspects an extra element is introduced to allow a three point external mounting and a four position mounting on the cold optics box. This 'Balance Arm' element is extremely stiff, while its mass is negligible.

This can be achieved using the ASTRON extreme light-weighting technique, resulting in more stiffness by maintaining both front and rear surface of the material. These structural shapes can be made using commonly available production machines and production software tools. Compared to conventional light-weighting techniques the new technique allows for light-weighting percentages of over 90% while at the same time increasing stiffness in bending and torsion by more than 50% [Ref. 4 and 5].

A high degree of light-weighting requires full control over the five degrees of freedom in the milling machine. Large internal volumes (pockets) are created by milling through small entrance holes. The next step is to create the pockets from two or more sides in such a way that they will form an efficient structure that suits the requirements of the design such as size, weight, stiffness and strength. The possibility to produce thinner walls (0.3 mm) than by using conventional milling strategies, makes the light-weighting even more efficient. Extra internal ribs are left in the pocket for improved stiffness, as can be seen in figure 8.

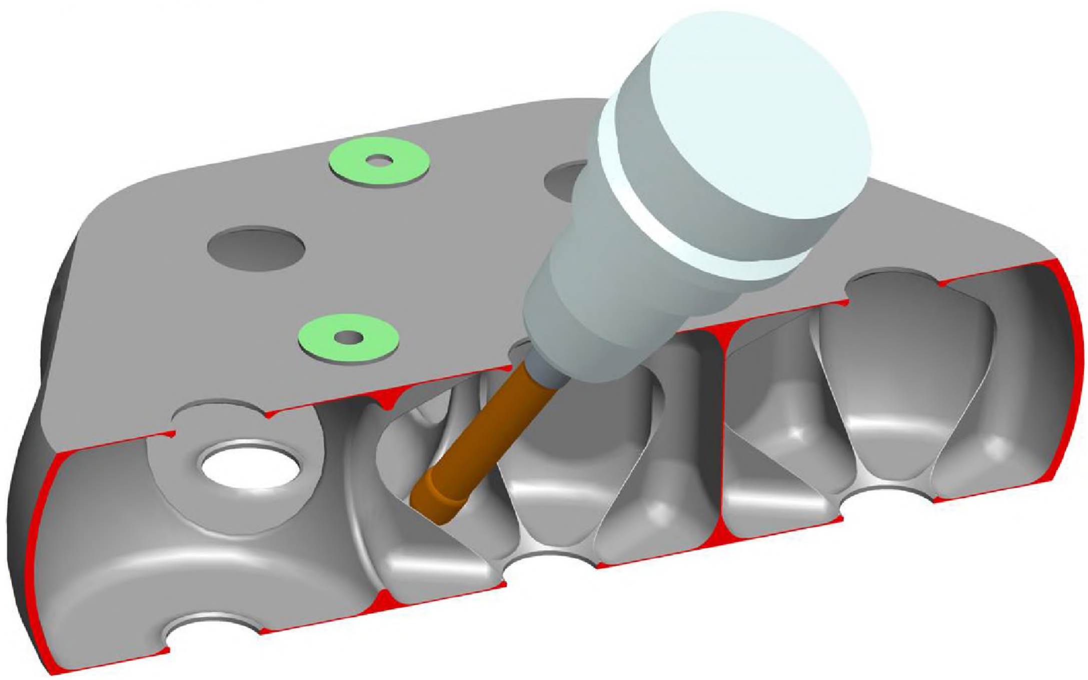

Fig. 8. In the ASTRON extreme light-weighting technique, large internal volumes (pockets) are created by milling through small entrance holes. This improves the stiffness to weight performance by 50% with respect to conventional light-weighting techniques. Internal ribs in the pockets improve the overall stiffness.

Extreme light weighting is a suitable production technique for the aluminium balance arm. The structural shapes in the design are closely linked to the extremes of five-axis milling; however the production of this element is possible on any standard five-axis milling machine. Existing milling strategies are not very efficient at excavating large internal volumes through a relatively small entrance hole. ASTRON has developed techniques to improve the milling efficiency.

5. ALUMINIUM MIRROR POST-POLISHING

The largest mirror used in the X-shooter NIR Spectrograph is 300 mm in diameter. This mirror, like the other mirrors in the cold optics box, is conventionally light-weighted (open back) in order to reduce its mass, while improving the mass to stiffness ratio.

An elaborate heat treatment process is used in order to minimize global deformation by aging in time. The process consists of solution treatment, down- and up-hill quench, aging and several thermal cycles [Ref. 6]. This process is used for the mirrors and the grating. For the mechanical structure it will suffice to age and thermally cycle.

In conventional techniques a nickel layer of several microns thickness (often ~30 microns) is applied to the aluminium mirror and subsequently polished. In combination with the light weighted mirror the CTE difference causes excessive deformation of the mirror surface (bimetallic effect). Alternatively the widely used diamond turning process can be used on bare aluminium, but causes a grating effect on the optical surface. This results in unwanted stray light.

In a newly developed technique the diamond-turned or bare aluminium mirror is post-polished to optical quality, preserving high shape accuracy at cryogenic conditions, while removing the grating effect and improving the surface roughness. Only on a small scale scratches still exist on the post-polished surface, but they are randomly distributed in all directions.

During the development of the aluminium post-polish process we found that the diamond-turning process causes shearing cracks due to splitting of the grains in the aluminium 6061-T6 material. In the post-polishing process these chopped grains are removed from the surface, introducing pits. Later on in this process these pits are filled with smeared aluminium, leaving a smooth surface of improved surface roughness and optical quality as can be seen in figures 10 to 13. This is confirmed by optical tests of the spot of a diffracted laser beam, as shown in figure 9.

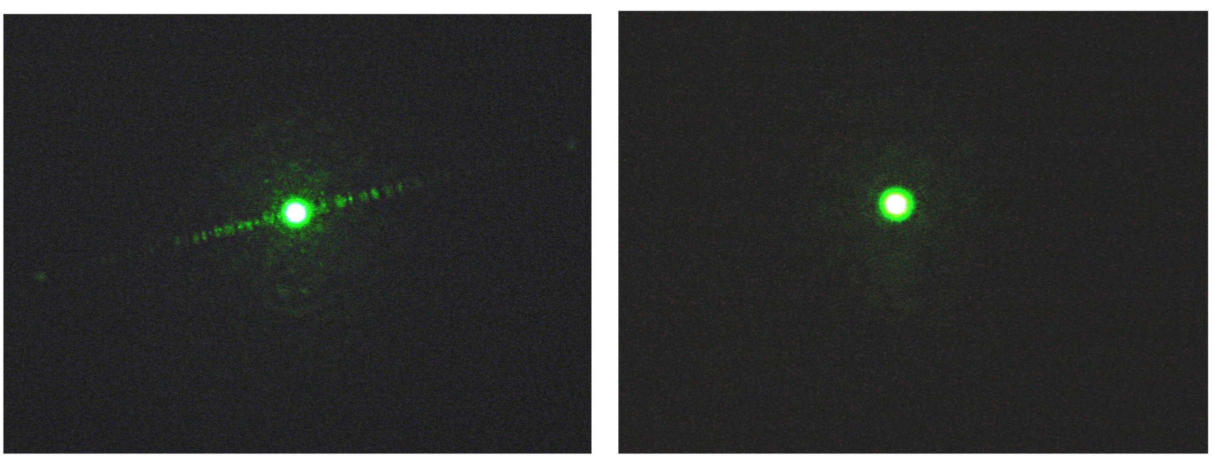

Fig. 9. Spots of a diffracted laser beam. The spot on the left shows the optical effect of the grating structure on the optical surface of a diamond-turned aluminium mirror. The spot on the right is from a post-polished aluminium mirror and shows less stray light.

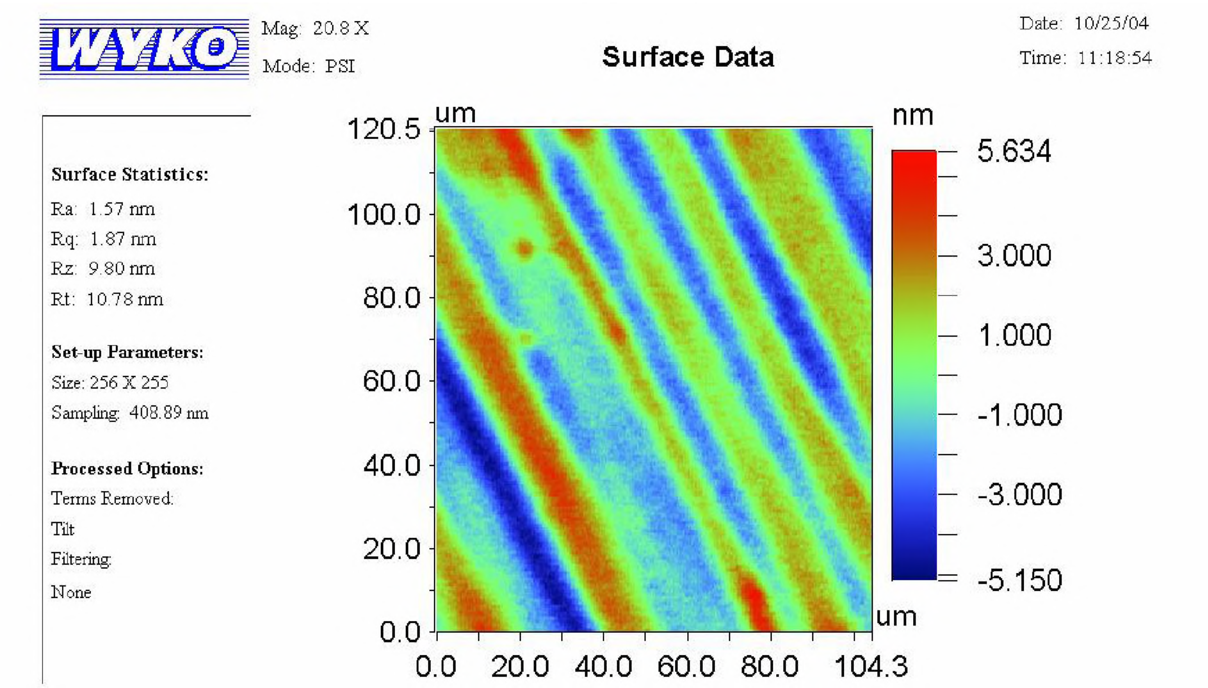

Fig. 10. Micro-roughness on a diamond-turned aluminium mirror showing the grating effect (100 x 120 µm).

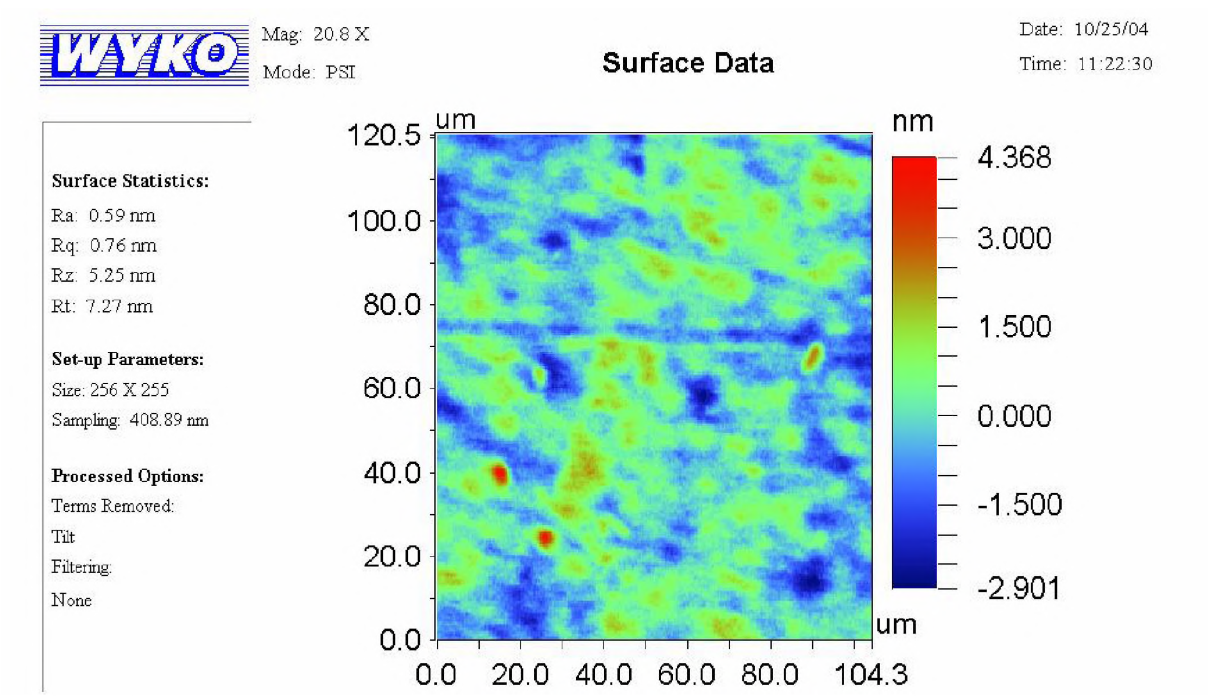

Fig. 11. Micro-roughness on a post-polished aluminium mirror (100 x 120 µm). The small spots in the lower left are most probably dust particles.

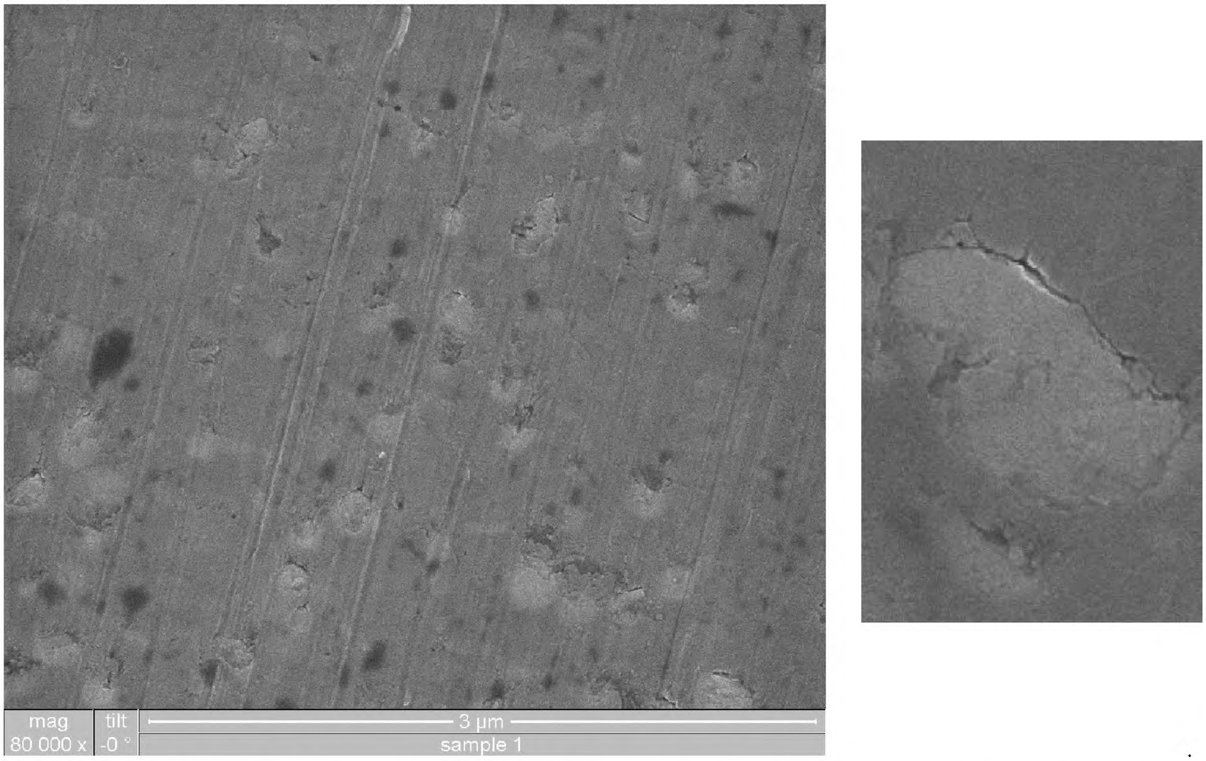

Fig. 12. Scanning Electron Microscope (SEM) image of a diamond-turned aluminium mirror (4 x 3 µm). Grains in the aluminium material are visible as lighter spots. Diamond-turning causes cracks at the top right side of these grains.

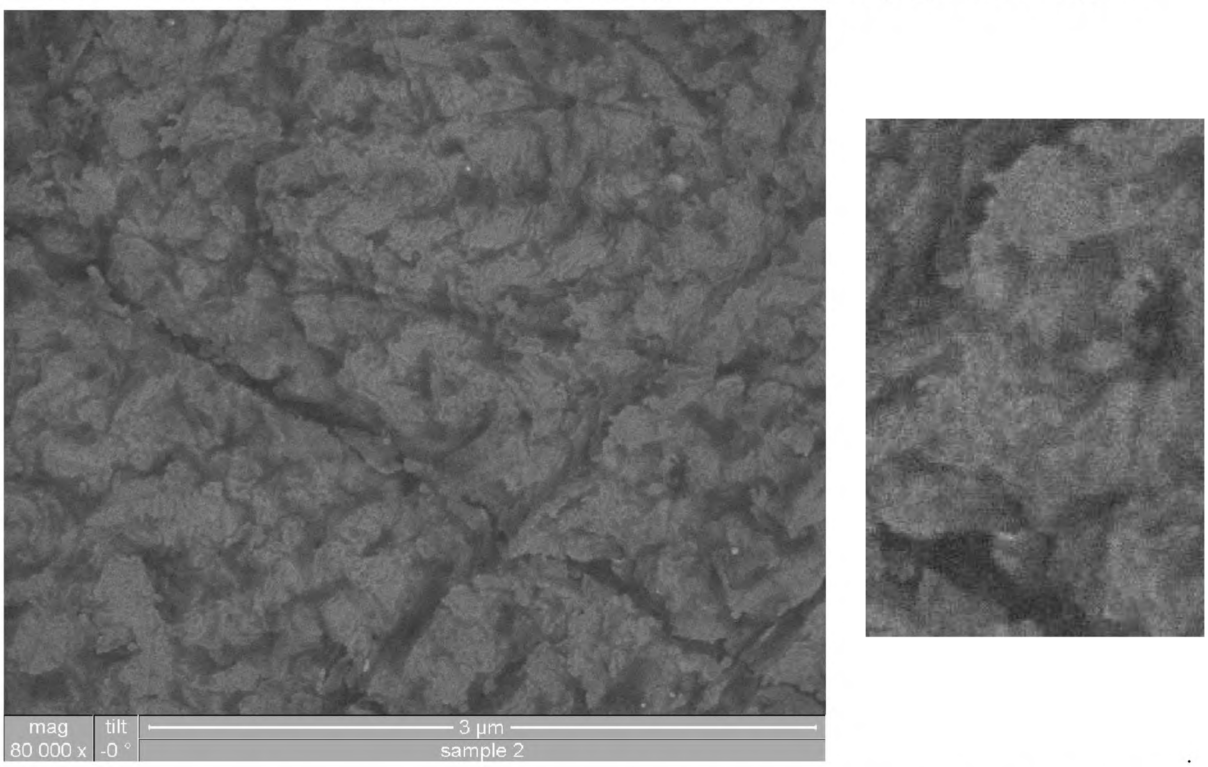

Fig. 13. Scanning Electron Microscope (SEM) image of a post-polished aluminium mirror (4 x 3 µm). The cloudy pattern in this image shows smearing effects caused by the post-polishing, leaving a smooth surface.

6. CONCLUSION

Several techniques have been developed at ASTRON in order to design the X-shooter NIR Spectrograph to the sometimes contradicting specifications. The techniques discussed in this paper contribute to the performance of the instrument regarding mass, stiffness, deformation, position stability, stray light and cool down time. A lot of effort has been put in the design to guarantee a virtually alignment-free integration of the instrument.

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