The LINC-NIRVANA Fringe and Flexure Tracker: Cryo-Ambient Mechanical Design

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ABSTRACT

The correction of atmospheric differential piston and instrumental flexure effects is mandatory for interferometric operation of the LBT NIR interferometric imaging camera LINC-NIRVANA. The task of the Fringe and Flexure Tracking System (FFTS) is to detect and correct these effects in a real-time closed loop.

Being a Fizeau-Interferometer, the LBT provides a large field of view (FoV). The FFTS can make use of the large FoV and increase the sky coverage of the overall instrument if it is able to acquire the light of a suitable fringe tracking reference star within the FoV. For this purpose, the FFTS detector needs to be moved to the position of the reference star PSF in the curved focal plane and needs to precisely follow its trajectory as the field rotates. Sub-pixel (1 pixel = 18.5 micron) positioning accuracy is required over a travel range of 200mm x 300mm x 70mm. Strong are the constraints imposed by the need of a cryogenic environment for the moving detector.

We present a mechanical design, in which the Detector Positioning Unit (DPU) is realized with off-the-shelf micro-positioning stages, which can be kept at ambient temperature. A moving baffle will prevent the intrusion of radiation from the ambient temperature environment into the cryogenic interior of the camera. This baffle consists of two nested disks, which synchronously follow any derotation- or repositioning trajectory of the DPU. The detector, its fanout board and a filter wheel are integrated into a housing that is mounted on top of the DPU and that protects the FFTS detector from stray light. Long and flexible copper bands allow heat transfer from the housing to the LINC-NIRVANA heat exchanger.

Keywords: LBT, LINC-NIRVANA, fringe tracker, mechanical design

1. INTRODUCTION

The Large Binocular Telescope,[1] with its two 8.4m telescopes on a common mount, allows for a unique combination of high angular resolution, large field of view (FoV), and the sensitivity corresponding to a light collecting area of 110m^2. It forms the bridge from current 8-10 m class telescope to future extremely large telescope technology. LINC-NIRVANA[2] (Fig. 1), the NIR interferometric imaging camera for the LBT incorporates the advantages provided by the design of the LBT. Because it obeys specific geometric constraints that constitute a Fizeau interferometer, LINC-NIRVANA can profit from the resulting large FoV in two ways: It allows for a large interferometric science FoV (limited by the cost of NIR focal plane arrays). And it allows to exploit the FoV to choose from a large pool of off-axis reference stars for adaptive optics and fringe tracking. In it's final level of implementation, LINC-NIRVANA will be equipped with a multi-conjugate adaptive optics system (MCAO) that can gather the light of reference stars in a 6 arcminute diameter field. In terms of angular resolution LINC-NIRVANA will outperform the imaging capabilities of exiting 8-10 m class telescopes by a factor of ∼3.

The Fringe and Flexure Tracking System (FFTS) is an integral part of LINC-NIRVANA. Its purpose is the real-time detection and compensation of differential piston between the two interferometric channels and the correction of misalignment due to instrumental flexure. A general description of the FFTS can be found in Straubmeier et al.[3]

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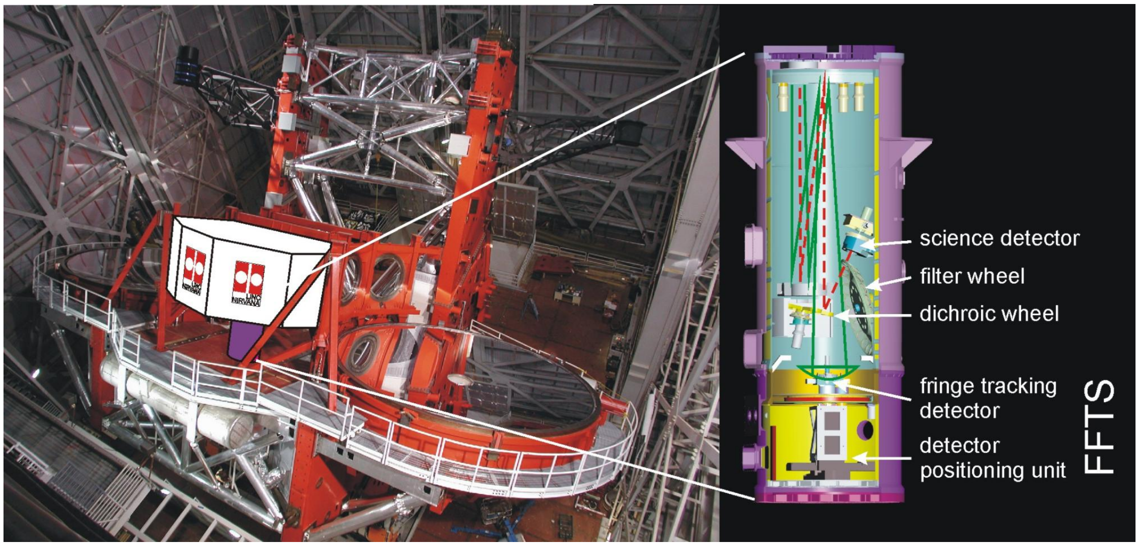

Figure 1. LINC-NIRVANA will be installed at one of the interferometric focal stations of the LBT. The two beams of the interferometer will be combined by a cassegrain telescope within the dewar[5] of LINC-NIRVANA. The fringe tracker is located at the bottom end of the dewar, close to the science detector. A set of dichroic beam splitters will reflect part of the NIR spectrum in the center of the FoV to the science detector. The remaining NIR radiation in the center is transmitted to the fringe tracker. In the FoV exceeding the central 10 arcsec., the full NIR spectrum is available to the fringe tracker.

The FFTS can make use of the large FoV and increase the sky coverage of the overall instrument (cf. Bertram et al.[4]), if it is able to acquire the light of any suitable fringe tracking reference star within the FoV. For this purpose, the FFTS detector needs to be moved to the position of the reference star PSF in the focal plane.

The FFTS will acquire images of this PSF at frame rates of up to 200 Hz. These frame rates can only be achieved for a small subwindow of the FFTS detector. In order to be able to continuously acquire the light of the guide star, the FFTS detector subwindow needs to follow the trajectory of the PSF in the focal plane. A recurring repositioning of the detector followed by a continuous shifting of the subwindow on the stationary detector itself was considered to be not feasible for many reasons (such as detector size, readout speed, clock-pattern upload). Therefore, the detector chip with a fixed subwindow has to be moved continuously along the PSF trajectory (note that it can stay fixed for an on-axis reference). The fringe tracking performance is dependent on the level of precision to which the position of the PSF on the subwindow is known.[4] Therefore, it is desirable to keep deviations from the actual position of the PSF due to positioning inaccuracies of the detector as small as possible. Subpixel (1pixel = 18.5m) positioning accuracy of the detector is a challenge for any positioning device with a large travel range like in this application. But much stronger are the constraints imposed by the need of a cryogenic environment for the detector. After intense studies and negotiations with companies that have experience in the field of micro positioning, building a cryogenic positioning device that provides the required accuracies had to be considered as unfeasible in the framework of this project. As a consequence, the detector has to be mechanically connected to, but thermally isolated and shielded from, the positioning device, which needs to be kept at ambient temperature. In this way, standard off-the-shelf micro positioning stages can be implemented, and accuracy can be achieved without extra engineering cost. In the following, we describe the mechanical design which we see as solution for the FFTS mechanics.

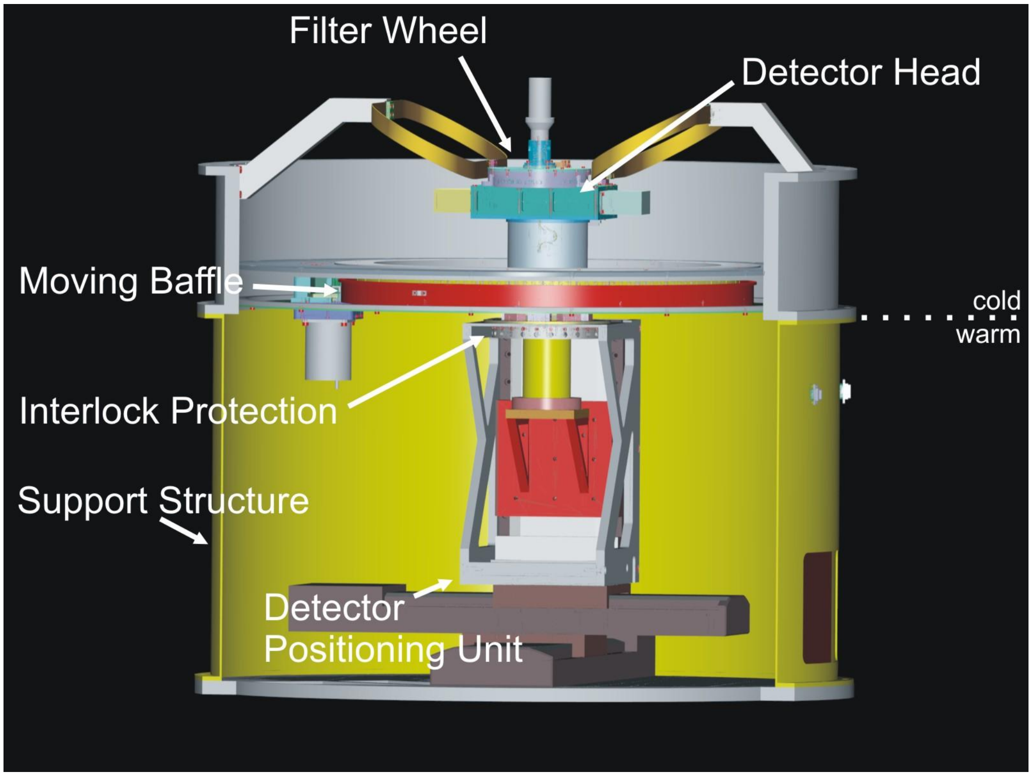

Figure 2. Main components of the FFTS hardware.

2. FFTS HARDWARE

The FFTS Hardware consists of the following components

- Detector Head with FFTS detector, detector fanout board, and filter wheel.
- Moving Baffle. Comprises the boundary between the cryogenic environment within the LINC-NIRVANA camera dewar and the ambient temperature environment of the Detector Positioning Unit.
- Detector Positioning Unit. A remote controllable 3D-stage with high positional reproducibility that allows us to position the detector anywhere within the usable FoV and follow fringe tracking guide star trajectories.
- Interlock protection. This prevents mechanical damage of the hardware in case of erroneous asynchronous motion of the Moving Baffle and the Detector Positioning Unit.
- Support structure. The mechanical outer skeleton of the FFTS to which the Moving Baffle and the Detector Positioning Unit are mounted.
- Control and image analysis computer. All realtime tasks such as detector positioning, PSF image processing and analysis, differential piston determination and piston mirror control will be carried out by a 4 CPU Linux workstation.

2.1. Detector Head

The Detector head contains the FFTS detector with its fanout board and the filter wheel. It is mounted on top of the fiberglass tube of the Detector Positioning Unit and has to fulfill the following requirements:

- Freely placeable along the curved focal plane in the range of the usable FoV.

- Flexible thermal contact to LINC-NIRVANA heat exchanger. Total constant heat load on Detector Head: < 1W. Temporary increase of heat load through filter wheel motor.
- Light-tight enclosure of detector and fanout board to shield stray light.
- Fixed orientation of the detector with respect to the direction of maximum resolution.
- Easy to remove. The Detector Head must be removable in order to access the warm part of the FFTS mechanics.
- Compact, lightweight design to reduce mechanical flexure of DPU.

As shown in Figure 3, thermal contact to the LINC-NIRVANA heat exchanger is provided via 4 flexible copper cooling straps made of many thin layers. The sandwich sheet structure (no braids are used) prevents the straps from hanging down, their length allows the detector head to access any point in the specified volume. Within the housing, a copper braid directly connects the cooling block at the bottom side of the fanout board with the cooling straps and provides direct heat transfer from the fanout board to the LINC-NIRVANA heat exchanger (cf. bottom left panel of Figure 3). The size of the housing allows us to mount the fanout board in four positions, hence allowing the selection of the detector quadrant which is to be placed underneath the opening to the filter wheel. All cables enter the box through the fiberglass tube of the DPU. Dismountable covers allow easy access to the cable connectors of the fanout board. Once the cables are unplugged, the whole Detector Head assembly, including the fanout board, can be removed from the base plate.

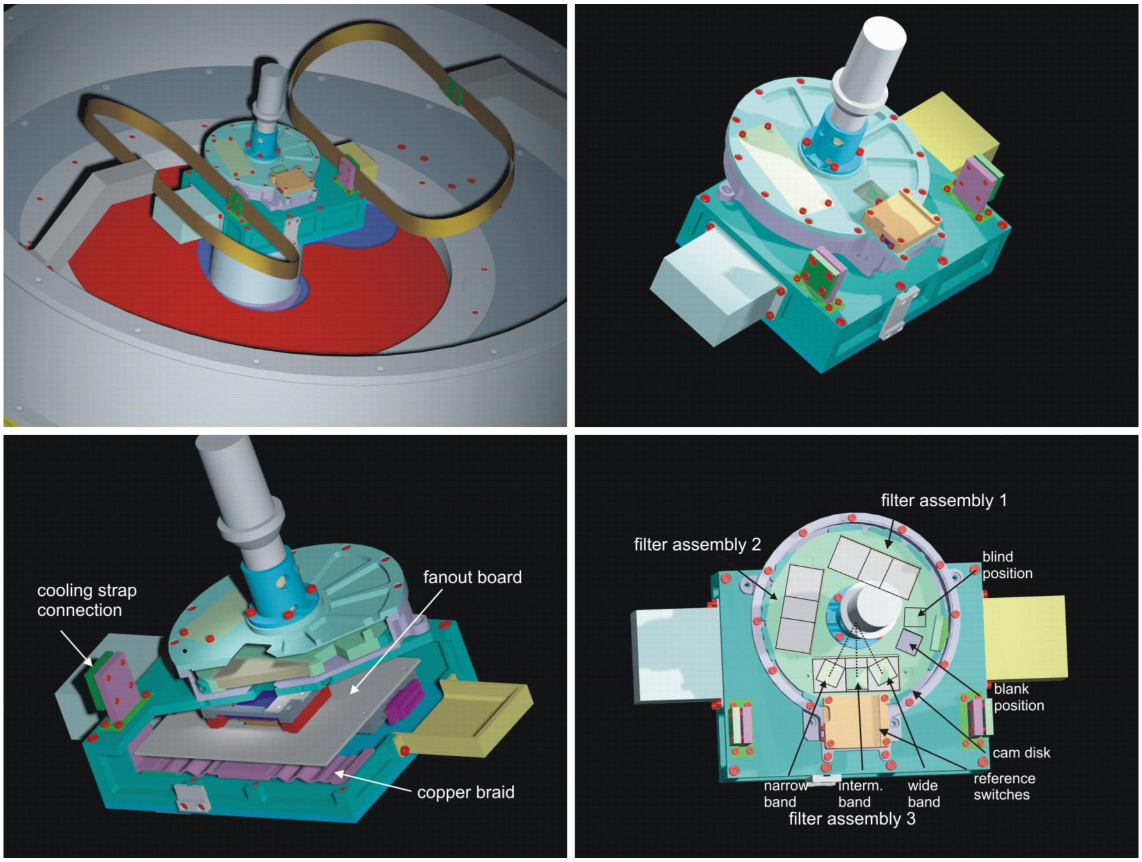

Figure 3. top left: Flexible copper bands provide thermal connection of the detector head with the heat exchanger. top right: the filter wheel is driven by a cryogenic stepper motor. bottom left: Fanout board with Hawaii I detector underneath filter wheel. bottom right: Filter assembly arrangement and position encoding by cam disks and micro switches

The filter wheel should provide 9 filter positions with filter central wavelengths of J,H and K and 3 different bandwidths. The design should include

- the possibility to rapidly change between filters of identical central wavelength but different bandwidths. During the alignment of the instrument, the search for the white-light fringe will start with a narrow band filter. Once the OPD is smaller than the coherence length of a filter, the filter will be changed to one with a broader bandwidth, to increase throughput and reduce coherence length. The time of vignetting of the detector readout window during such a change should be less than the time constant of atmospheric piston.
- reference switches for filter position detection.
- a blank and a blind position.

To allow for a minimum time of vignetting, filter assemblies are used. 3 Filter assemblies are required. Each includes 3 filters with identical central wavelength but different bandwidths. Within each assembly, the filters have to be ordered with ascending bandwidth (say from left to right). Each assembly consists of rectangular filters which are connected in a row (cf. bottom right panel of Figure 3). All three assemblies will be part of a common filter wheel. The overall dimensions of the assembly are chosen such that the clear aperture of the left and right filter still covers the detector area, since the centers of these filters do not have the same radial distance to the filter wheel rotation axis as the central filter.

2.2. Moving Baffle

The Moving Baffle separates the cryogenic environment of the dewar from the ambient temperature environment. It prevents intrusion of thermal radiation into the interior of the camera. Furthermore, it has to allow the DPU to access the cryogenic environment via a hole, which can be moved to any position within the region of the focal plane projected to the baffle plane that corresponds to the usable FoV. The following requirements have to be fulfilled:

- Light tight baffle. The shield has to suppress the intrusion of NIR photons into the camera environment.
- Moving access hole. The area of the FFTS FoV projected onto the XY reference plane of the baffle has to be accessible by the moving access hole. This hole allows the DPU to access the cryogenic environment.
- Baffle and DPU should be mechanically decoupled. The baffle system should not add additional gravitational force or vibrations to the fiberglass tube of the Detector Head.
- Synchronous motion of DPU and Moving Baffle.
- Cold shield. The shield has to prevent the intrusion of thermal photons into the cryogenic environment of the dewar. This includes photons radiated from the shield itself. The science detector is oriented in a way that it is facing the moving shield. Emitted or unshielded photons will directly increase the background of the detector. Therefore the shield itself has to be cooled.
- Compact design. The baffle should not define the radius of the dewar.

The Moving Baffle consists of two nested disks (cf. Figure 4). The outer disk is centered on the symmetry axis of the DPU. It is guided by a Kaydon Thin-Section ball bearing that provides a central clearance with a diameter of 406mm, i.e.a clearance that is larger than the positioning range of the DPU. This disk needs to be moved synchronously with the DPU. It covers the full area which needs to be accessible, except for a narrow circular arc shaped opening. This opening is covered by the second disk, which is located inside the double layered outer disk (cf. bottom left panel in Figure 4). The inner disk allows for radial positioning of the DPU. The inner disk can be moved by the DPU itself without active drive mechanism (a balanced mass distribution and a constant distance to the disk's center results in a constant torque which is dependent only on the friction of the ball bearing. Furthermore, there will be no radial movement while tracking a reference source). The outer disk, however, needs to be driven by a cryo motor (cf. right panels in Figure 4), since the torque is dependent

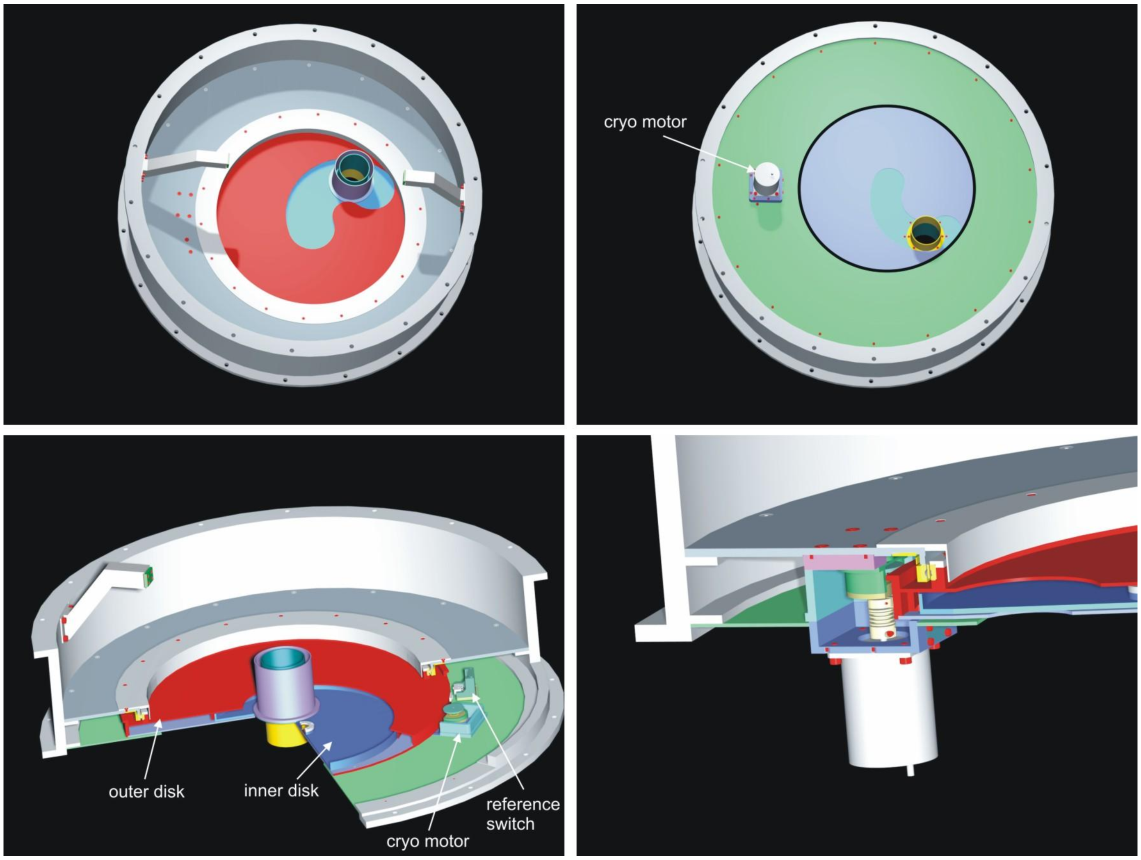

Figure 4. top left: Moving Baffle, view on cold side. top right: Moving Baffle, view on warm side. The outer annulus is in thermal contact with the heat exchanger. Radiation heat transfer on the rotating disk is restricted to the encircled surface in the center. bottom left: Two nested disks shield the cold part from the warm. The vertical tube can be positioned everywhere within a radius of 150 mm from the center of the baffle by rotating the two disks. bottom right: A Phytron stepper motor moves the outer disk of the baffle.

on the radial position of the DPU. The Baffle motion has to be synchronized with the DPU motion. The design permits a positional discrepancy of 3 mm before triggering an interlock of the system. With this concept, any X-Y motion of the DPU is decomposed into two simple rotations. In the most common case of tracking a guide star, only circular trajectories centered on the DPU symmetry axis are followed, hence the number reduces to one rotation. The constraints upon the precision of the baffle motion is low due to the +/- 3 mm tolerance. In contrast to translational motion at cryogenic temperatures, rotational motion is easier to realize in such an environment. The current design assumes sufficient heat transfer via the ball bearing. Tests with a prototype have suggested that this approach is reasonable. Further tests are currently carried out for final confirmation (cf. Figure 6, panel 5). To secure the heat transfer in the cool-down period, the outer and not the inner rim of the bearing is attached to the heat exchanger. Differential contraction in radial direction therefore needs to be compensated to prevent the destruction of the bearing (cf. Fig. 5).

To minimize the radiation heat load onto the outer disk, all parts that do not interfere with the DPU are covered by a cold plate. Also, the surface of the disk facing the warm side will be coated to reduce absorption.

2.3. Detector Positioning Unit

The DPU allows to move the Detector Head along the focal plane to the position of the reference source and to follow its trajectory. The following requirements have to be fulfilled:

- Travel range 200 mm x 300 mm x 70 mm.

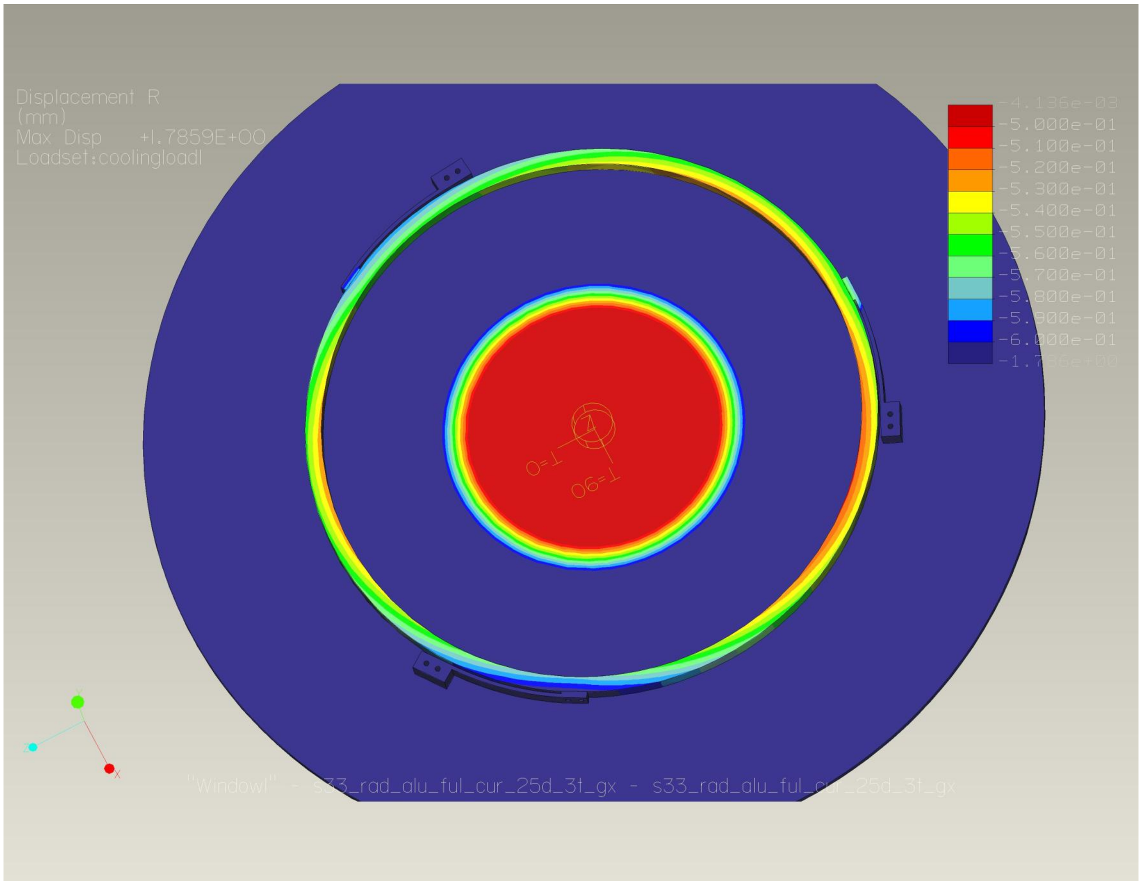

Figure 5. FE analysis of the bearing mount concept with flexible spacers. They allow for differential contraction in radial direction. Shown is the radial displacement of a setup consisting of a steel mount, aluminium spacers and an aluminium baseplate at a temperature of 70K and a gravitational load of 50N in vertical direction in the image plane. The goal of this FE study was to dimension the radial spacers and the bearing mount in a way that the center of the mount remains within 0.1mm of the warm position. In addition, any non-radial deformation of the mount must remain within the tolerances of the bearing.

- Maximum velocity for guide star tracking: 2.6 mm/s. This corresponds to the radial velocity of the sky rotation at a radius of 150 mm from the optical axis and telescope pointing with zenith distance of only 1°.
- Absolute positioning accuracy: $<50\mu$m (for initial PSF position acquisition).
- Position reproducibility: +/- 4μm for PSF trajectory tracking. The quality of fringe tracking depends on the uncertainty of the PSF position. Knowing the central position of the PSF to sub-pixel precision allows us to reduce the number of free parameters that have to be fitted to the PSF profile, which in turn increases the performance of the fringe tracking algorithm significantly.[4]
- Qualified for vacuum conditions (10^{-6} mbar).
- Routing of all cables to the Detector Head through the DPU.
- Shielding of the Z-direction travel range below the Detector Head.

The DPU consists of 3 vacuum qualified micro positioning stages from Physik Instrumente (PI) with travel ranges corresponding to the volume that has to be accessible by the detector (cf. Figure 6, panel 1 and 6).

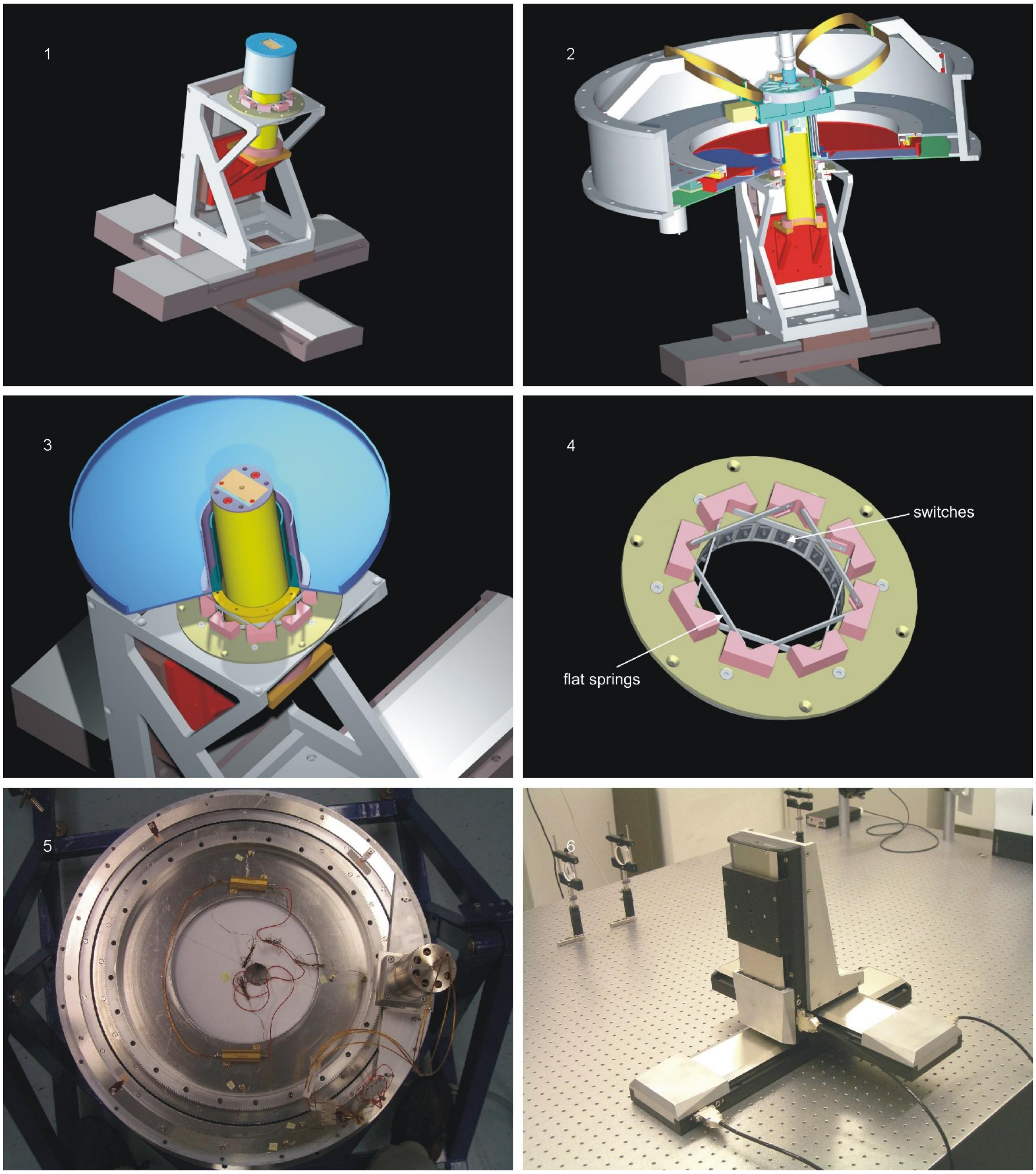

Figure 6. 1: The Detector Positioning Unit consists of 3 linear stages which allow positioning of the detector head anywhere within a volume of 200 x 300 x 70 mm^3. 2: A fiberglass tube supports the detector head in the cryogenic part and connects it with the linear stages in the warm part of the dewar. 3: Flat springs attached to the Detector Positioning Unit center the inner disk of the moving baffle on the tube axis. The detector head and the baffling tubes for motion in Z direction can be completely removed to disassemble the FFTS mechanics. 4: 24 microswitches form a two level interlock protection. The flat springs center the inner disk of the baffle on the tube axis and allow for passive movement of the disk. 5: The heat transfer via a Kaydon Thin-Section ball bearing is currently tested in a LN$_2$ dewar at the University of Cologne. 6: 3 linear stages from PI are assembled in a test setup for the Detector Positioning Unit.

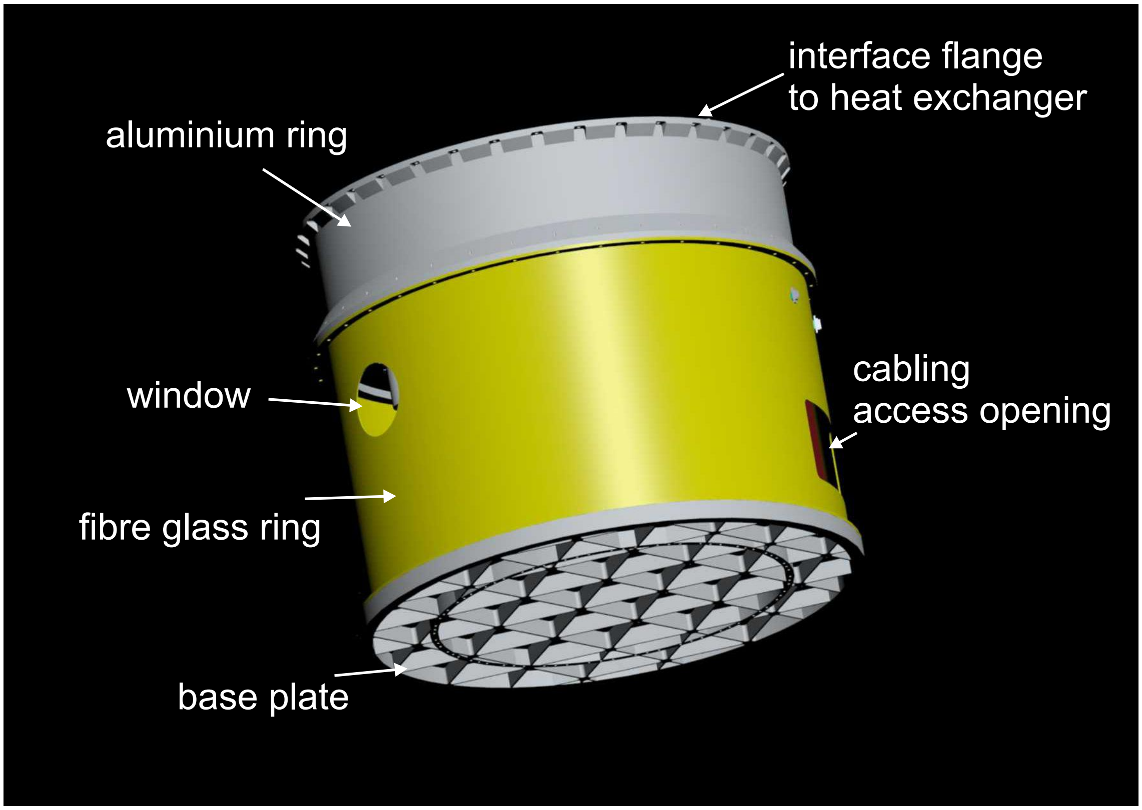

Figure 7. The support structure consists of a aluminium ring in the top, cold part, a fiberglass ring in the warm, bottom part, and a base plate.

A vertical fiberglass tube mounted to the Z-stage points through the moving hole in the baffle and carries the Detector Head (panel 2). The travel range in Z-direction is shielded by a double layer shield of axial tubes. Tangential flat springs attached to the top of the Z-stage center the inner disk of the moving baffle around the fiberglass tube (panel 3 and 4). A photon-tight cable feedthrough is integrated into the fiberglass tube. This has the advantage that all cables and the feedthrough itself can remain assembled when disassembling the Moving Baffle.

An interlock protection is foreseen to prevent damage to the hardware in case of uncoordinated motion of DPU and Moving Baffle (panel 4).

2.4. Support Structure

The support structure (cf. Fig. 7) is the mechanical outer skeleton of the FFTS. In the upper part, it supports the Moving Baffle (cf. Sect. 2.2), hence it forms the boundary between the cryogenic environment and the ambient temperature environment of the LINC-NIRVANA dewar. Its design has to include thermal insulation between these two environments. It also includes the mounting and thermal interface to the LINC-NIRVANA heat exchanger. Its main purposes are:

- mounting platform for the ambient temperature DPU.
- thermal bridge between cryogenic FFTS components and the LINC-NIRVANA heat exchanger.
- mechanical interface to LINC-NIRVANA dewar (heat exchanger).

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