The LUCIFER MOS: a full cryogenic mask handling unit for a near-infrared multi-object spectrograph

Peter Buschkamp*[a], Reiner Hofmann[a], Hans Gemperlein[a], Kai Polsterer[b], Nancy Ageorges[a], Frank Eisenhauer[a], Reinhard Lederer[a], Mathias Honsberg[a], Marcus Haug[a], Johann Eibl[a], Walter Seifert[c], Reinhard Genzel[a]

[a] Max-Planck Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany;
[b] Astronomisches Institut Ruhr-Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany;
[c] Landessternwarte Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany

ABSTRACT

The LUCIFER-MOS unit is the full cryogenic mask-exchange unit for the near-infrared multi-object spectrograph LUCIFER at the Large Binocular Telescope. We present the design and functionality of this unique device. In LUCIFER the masks are stored, handled, and placed in the focal plane under cryogenic conditions at all times, resulting in very low thermal background emission from the masks during observations. All mask manipulations are done by a novel cryogenic mask handling robot that can individually address up to 33 fixed and user-provided masks and place them in the focal plane with high accuracy. A complete mask exchange cycle is done in less than five minutes and can be run in every instrument position and state reducing instrument setup time during science observations to a minimum. Exchange of old and new MOS masks is likewise done under cryogenic conditions using a unique exchange drive mechanism and two auxiliary cryostats that attach to the main instrument cryostat.

Keywords: LUCIFER, LBT, NIR, spectrograph, MOS, multi-object-spectroscopy, cryogenic, robotics

1. INTRODUCTION

LUCIFER is the novel near-infrared camera and multi-object spectrograph at the Large Binocular Telescope on Mt. Graham, Arizona. It features a unique multi-object mask exchange unit for storing and loading the spectrometers masks, the MOS-unit. It has been developed mainly by the Max-Planck Institute for Extraterrestrial Physics in Garching in collaboration with the other LUCIFER consortium partners, most notably here the Astronomical Institute of the University of Bochum for the MOS control software part.

The LUCIFER instrument is now in regular science operations since fall 2009, with the MOS unit offered for science users since beginning of 2010. So far over 3000 mask exchanges have been run in final hardware configuration during commissioning, test and science nights. Most of the occasionally occurring errors could be corrected using build-in recovery functions, a small fraction however also required engineering intervention which subsequently lead to hardware upgrades during two scheduled maintenance runs. See Seifert 2004 and 2010 [3, 4] and Ageorges 2010 [5] for a summary of the instrument and results from the instruments commissioning.

In this paper we describe and show the unit 'as build'. In this configuration it is now in use since Summer 2009 with some few modifications introduced after commissioning and some time of operations to enhance motion-auto-correction capabilities and reliability of the unit. We refer to our previous papers, Hofmann et al. 2003 [1] and 2004 [2] for comparison and further CAD drawings.

Understanding the design of the MOS components is closely related to understanding the MOS operation as defined in the control software sequences. Because of this close relation between hardware and function (software), we will first present an overview of the functionality, followed by a description of the sub-units that are needed to realize these functions in section 2. In section 3 we take a closer look at the control components and close with a description of an exemplary motion sequence of putting a mask from the storage into the focal plane.

*Correspondence should be send to: Peter Buschkamp; email: buschkamp@mpe.mpg.de; phone +49 89 30000 3295

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 773579 · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857950

The MOS unit provides the following functions:

- storage of up to 33 masks
- reproducible positioning of a mask in the focal plane with an accuracy better than 30 µm
- transport of a mask between the storage cabinets and the focal plane unit,
- temporary removal of a mask from the focal plane (e.g. for pointing checks),
- replacement of the exchangeable cabinet with a cabinet containing new masks under vacuum and at operating temperature.

Except for the cabinet exchange all functions can be executed at any time, independent of the instruments rotation or tilt angle. We refer to Hofmann et al. 2003 and 2004 for a detailed description of the design process and how requirements originating from these needed functions were met during planning and construction.

2. MOS SYSTEM COMPONENTS

The MOS functions mentioned above have lead to the development of the following MOS components:

- a focal plane unit (FPU) to position and clamp a mask in the telescope field of view,
- a structure providing the interface to the LUCIFER structure and carrying all other MOS- components,
- a stationary and an exchangeable mask cabinet together with a drive unit and a locking mechanism for the exchangeable cabinet,
- a mask retainer locking the masks in the cabinets and releasing one mask for transport to the FPU,
- a mask handling unit (MHU) which takes the mask out of the cabinet, carries it to the FPU and inserts it into the FPU.

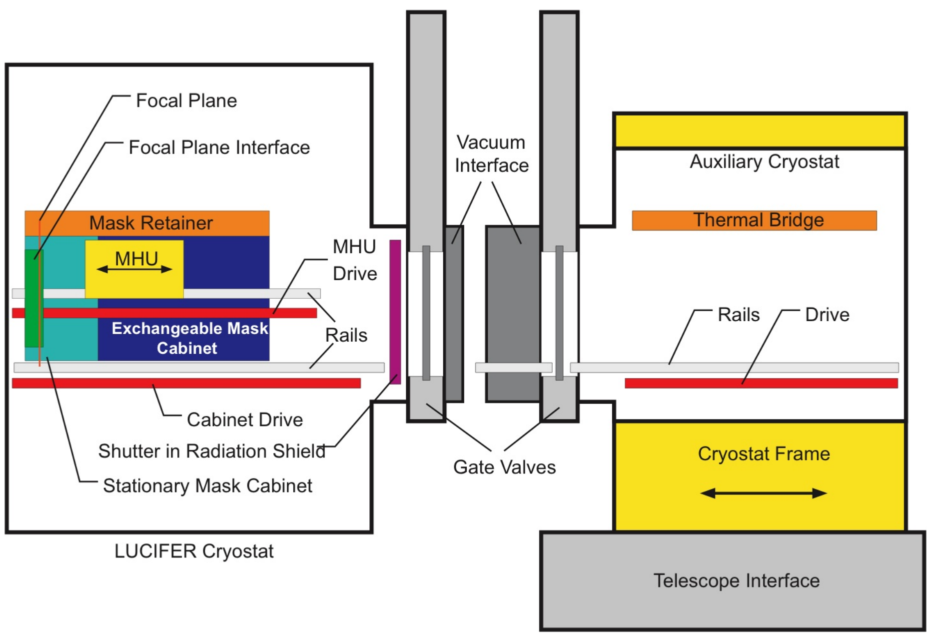

Figure 1: Schematic overview of the MOS system components; see text for details

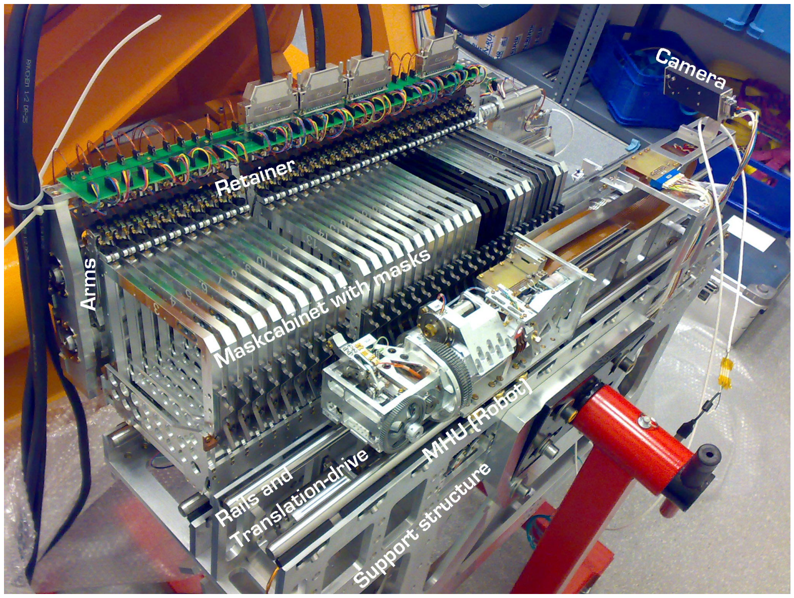

Figure 2: Storage and Mask Handling Unit during maintenance outside the main cryostat. MHU rotation head is in storage position with the grabber open, ready to grab a mask. The Focal Plane unit is not visible in this image. The silver mask frames have meanwhile all been replaced with blackened ones.

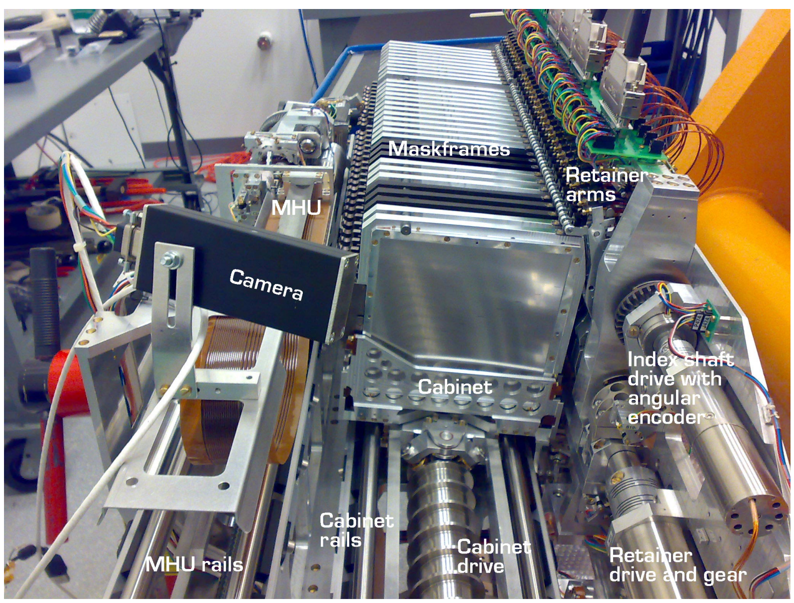

Figure 3: View as seen from the LUCIFER gate valve, the cabinet drive is visible in the front. On the right the motors for the index shaft and drive shaft of the retainer are visible.

For the mask cabinet exchange additional components are required: a radiation shield shutter opens a port in the LUCIFER radiation shield through which the cabinet is transferred into two auxiliary cryostats equipped with drive units for the cabinet transfer and gate valves identical to the one attached to LUCIFER.

2.1 Focal plane masks

For the global functionality of the LUCIFER instrument, the focal plane slit masks are the essential components of the MOS-unit. At any time up to 33 masks can be stored inside the main instrument cryostat. This set of masks is distributed over two cabinets: One cabinet is fixed inside LUCIFER and houses 10 permanent masks i.e. longslit masks with slitwidths from 1.0 to 0.25 arcsec as well as alignment, test and field stop masks. The second cabinet has 23 storage slots for user-provided MOS masks. This cabinet is usually is exchanged monthly prior to an scheduled observing block.

A masks consists of a mask frame and the mask sheet, which is held therein. The instrument side (as seen by the detector) of both frame and sheet are blackened. This is to reduce and diffuse light originating from reflections on optical surfaces. The mask frame has interfaces to the Mask Handling Unit (a 'handle'), to the Focal Plane Unit (two inside cones for centering the mask on the FPU's alignment pins) and to the storage unit (hardened surfaces for guiding and locking). Frames are 180x180mm, having a clear aperture of 144x144mm, corresponding to 4x4arcmin on sky. All masks are cylindrically curved in dispersion direction with a radius of curvature of 1030mm, following the telescopes field curvature in one dimension. A full 2D spherical correction for the masks would be hard to manufacture and it would be even harder to maintain the shape under cryogenic conditions given the thickness of the stainless steel mask sheet of 120 microns. The curvature is defined by the frames which are machined accordingly. To reduce the defocus on the edge of the mask and to get an overall more uniform focus, we limit the slit distance from the optical axis to +/- 1.25 arcmin in dispersion direction and place the mask center 0.5mm behind the telescope focal point. This reduces the maximum defocus to +/-0.5mm. Through this measure the usable FOV is reduced from 4x4 to 4x2.5armin in dispersion direction. This limitation is not too severe, keeping in mind that the spectrum of near-edge slits is clipped by the detector. Experience from first year operations has shown that no science program has suffered from this limitation.

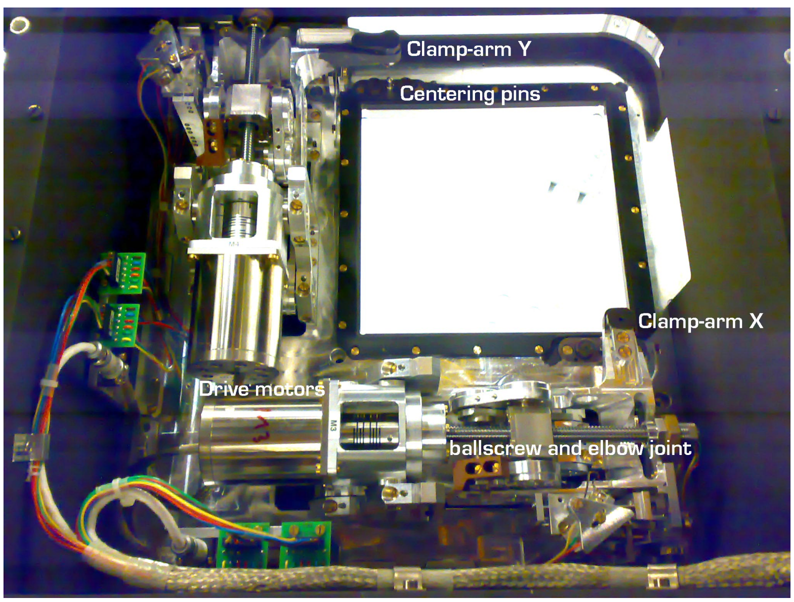

Figure 4: The Focal Plane Unit inside the cryostat. The black frame defines the FOV when no mask is present.

2.2 Focal Plane Unit

The Focal Plane Unit (FPU) is used to hold and position the mask in the focal plane. Masks are held and positioned using clamping arms and centering pins. In an earlier version described in Hofmann 2004, lateral alignment was done by moving centering cylinders in the mask frames onto centering pins with fitting diameter anchored in the FPU base-plate. During extended cold tests in few cases canting was observed. The design was changed to positioning-cones driven against positioning ball-cups, thus rendering canting impossible. Extended cold test proved this setup to be very reliable and accurate. In x-y-direction the masks can presently be positioned with an accuracy of < 30 microns, corresponding to < 0.05 arcseconds on sky. In z-direction along the optical axis the positioning accuracy is better than 100 microns.

The FPU has three operating states: OPEN, HOLD and LOCKED: When a mask is put into the focal plane it is first rotated into the FPU by the Mask Handling Unit (MHU, see next paragraph) into the gap between the clamp-arm tips and the centering pins of the FPU while the unit is in OPEN position, i.e. the clamp-arms are fully retracted. The centering pins are located close to diagonally opposite corners of the 150 mm square cutting of the FPU which is centered on the telescope axis. The pins end in the ball cups mentioned above and are met by cone-shaped openings of cylinders in the mask frames. After this insertion movement, the MHU pushes the mask onto the centering pins. Once the mask is in contact with two spring loaded pads located to the left and right of each centering pin, the two FPU clamps move downwards until their spring loaded tips hold down the mask (HOLD position). In this stage the pins only serve as a rough alignment and keep the mask frame from falling when released. Then the MHU grabber releases the mask, and finally the FPU clamps are completely closed, thereby pushing the spring loaded pads completely into the FPU base plate (LOCKED position). Now the alignment-surfaces which center the mask are in contact and align the mask correctly inside the FPU. The FPU clamps are elbow joints driven by ball screws. The mechanism provides self-locking of the clamps in LOCKED position.

Both clamp arm drives have three micro switches attached to them which indicate the OPEN, HOLD and LOCKED position, acting as motion cut-off limit switches for OPEN and LOCKED. To monitor the actual mask movement, reed-contacts are installed in the FPU which are actuated through magnets inside the mask frames to indicate if the mask is in or has actually reached the OPEN, HOLD or LOCKED position and whether it is safe to grab or release the mask.

2.3 Mask Handling Unit

The Mask Handling Unit (MHU) or 'robot' is the central component to move and manipulate the masks between the FPU and the mask storage. The MHU has three degrees of freedom for grabbing the mask, rotating the mask into the FPU and the storage cabinet and moving along the cabinet to the corresponding storage place or the FPU position. These three functions are carried out by three subsystems: the grabber, the rotating head ('rotator') and the body ('translator').

Grabber

Masks are picked up or put down with the MHU grabber. This subsystem grabs a mask frame on a handle that is mounted on the side of each mask frame. It works similar to locking pliers for secure transport of the mask between storage and FPU. The system is build up from a ballscrew driven elbow joint which is self-locking when the mask is grabbed. Motions are stopped by limit switches at both ends of the ballscrew. We detect whether or not a mask is grabbed through two strain gauges that measure the deformation of the elastic part of the elbow joint. To compensate for thermal effects on the strain gauges they are calibrated before each grabbing motion.

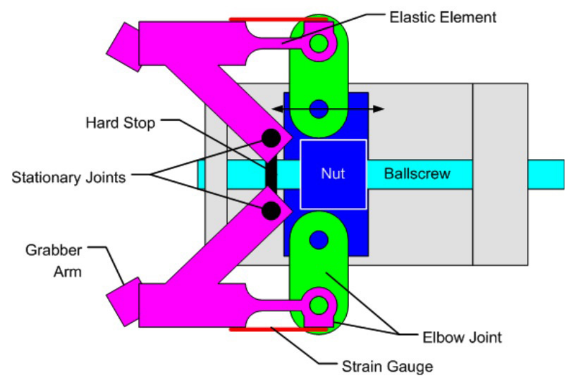

Figure 5: Schematic drawing of the grabber in dead center configuration. Moving slightly to the left selflocks the grabber.

Rotator

The general unit layout in Figure 8 shows the FPU and storage to be located opposite to each other, with the rail system of the robot between them. To get a mask out of the storage cabinet and into a position from where it can be moved along the cabinet towards the FPU and finally into the FPU the mask needs to be rotated (see Figure 11 for a snapshot of this motion). The rotation is done with the robots head, which also houses the grabber. The rotation axis is parallel to the translation direction. For a detailed description of the movement itself see the example in Section 3.5. There exist three rotation positions: The storage angle, under which masks are grabbed and released while they are in the storage cabinet, the transport and the FPU-angle. In transport position the mask is moved along the cabinet. The mask is also rotated in transport position for a short time, when the mask is temporarily removed from the FPU for pointing checks. Rotation can be locked in storage, transport or FPU position for security reasons.

The rotator motion is backlash free using a spring-loaded double gear wheel driving a larger wheel and is controlled using an angular encoder. Total gear ratio of the stepper motor is 1:60, giving us enough torque to move the mask in every instrument orientation and at the same time allowing us to fine-tune the position angles to 0.1 degree. Since the total angle between storage and FPU is only 185 degrees, we use absolute angles to address the target position. In earlier versions limit switches were used to define the three positions. However due to different instrument position-dependent torques on the head and grabber when a mask is grabbed a more flexible control solution using the angular encoder mentioned was implemented.

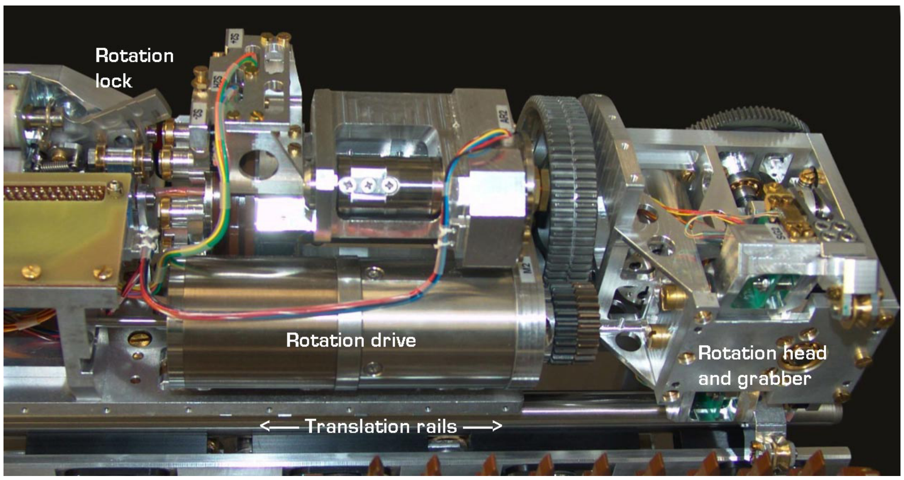

Figure 6: The Mask Handling Unit in storage position

Translator

Along the cabinet the robot does not move on its own but is rather pulled or pushed using long ballscrew and a nut that attaches to the robot's base plate. It rides on two stainless steel rails with gold-coated ball bearings as 15 wheels in 3 pairs. Their arrangement is two fold: Three guiders consisting of 3 wheels each on one side of the rails ensures precision movement. Opposite of each guider is a two-wheel arrangement that defines the azimuth angle over the other rail. This arrangement is insensitive to slight changes in the separation of the rails due to differential thermal contraction in cryogenic conditions. Motion is monitored through an angular and incremental encoder. The rails two end positions are equipped with limit switches. These are used to calibrate the zero point ('initialize') and measure the contraction between warm and cold instrument, which can then be accounted for by the control software. They also serve as motor power off switches when run into. Mask positions are counted as absolute stepper-motor steps from the zero point and are flagged with the associated ballscrew angle for control and possible self-correction. Like the rotator, the translation can be locked in two positions per revolution using a coil-actuated plate. The positions are set such that translation can be locked in OPEN and HOLD position when moving the mask inside the FPU.

2.4 Mask Storage

Masks are stored in a mask cabinet similar to such ones used in slide projectors to store slides in. As mentioned above, the masks are distributed over two cabinets: One cabinet is fixed inside LUCIFER and houses 10 permanent masks. It can only be replaced during maintenance of the instrument when warmed up. The second cabinet has 23 slots for user-provided MOS Masks. This one can be removed and replaced with the help of the auxiliary cryostats in instrument working condition, i.e. cold and evacuated. The mask storage consists of two subunits: the cabinet for storing and the retainer which holds the masks in place and allows access to individual masks even when the instrument is rotated and tilted.

Mask Cabinet

The mask cabinet stores the masks and is used to drive masks in and out of the Lucifer cryostat. Nominal slot pitch is 17mm with corresponding to 680steps (or 3.4 revolutions) of the MHU translator. Like the robot, the cabinet runs on rails with the same wheel pattern as the robot. Since during cabinet transfer the cabinet has to attach to and detach from the driving mechanism we don't use a ballscrew but a spiral screw to drive the cabinet. The cabinet attaches to the spiral screw with a set of wheels (see Figure 3 and 10). The spiral screw has an angular encoder attached that is needed for synchronizing its motion with another spiral screw inside the auxiliary cryostats during cabinet exchange. The cabinet structure is soft against torsion about its long axis to reduce stress during cabinet exchange introduced by misalignment of the three sets of rails carrying the cabinet in LUCIFER, the vacuum interface and the auxiliary cryostat. A clamping mechanism ensures that the cabinets reach the same end position every after cabinet insertion. Thus the mask positions in robot-translation direction are fixed and can be stored in a simple lookup table.

Retainer

In order to exchange masks in every instrument rotation and tilt, those masks that are not in use need to be locked in place in the cabinet. Also masks must be unlockable individually when a certain mask is to be put in the FPU, again, in every instrument orientation. This is the task of the retainer. It consists of 33 arms, one for each mask, which lock the masks in place or unlock one selected mask. For the cabinet exchange all masks can be unlocked simultaneously: The arm consist of two parts: The bottom part is bolted to the drive shaft, the top part is attached to the bottom with a flexible joint supported by springs. This arrangement is combined with an index shaft for the mask selection. The drive shaft rotates about 10 degrees from locked to unlocked. Which arm actually gets retracted is determined with the index shaft. For every arm there exists a circumferential bar on the index shaft with a notch. The notches are rotationally offset by 10.6 degrees between neighboring bars, with one additional notch on each bar with the same azimuth angle for all arms. To select a mask the index shaft is rotated to an angle that corresponds to a specific arm. All arms are driven backwards against the index shaft and their circumferential bars. For one arm the notch is now in the correct position and a blocking bar build into the arm can move into this notch and the arm can move backwards. The blocking bars of all other arms do not fit into their respective notches at that point. For these arms the springs in the arms bottom part are compressed while the two sections flex around their joint, but the arms do not retract while the drive shaft turns further on towards its end position. Thus these arms do not free their masks but stay in locked position. All arms have magnets attached to their top which activate reed contacts when retracted to monitor locked and unlocked status. A second micro switch on each arm gets activated upon mask contact, indicating the presence of a mask in a given slot. The total force on the drive shaft when only one mask retracts is around 250Nm. This is more than enough to easily permanently damage an arm in case of malfunction. Therefore several security features have been added as well as various checks in the control software.

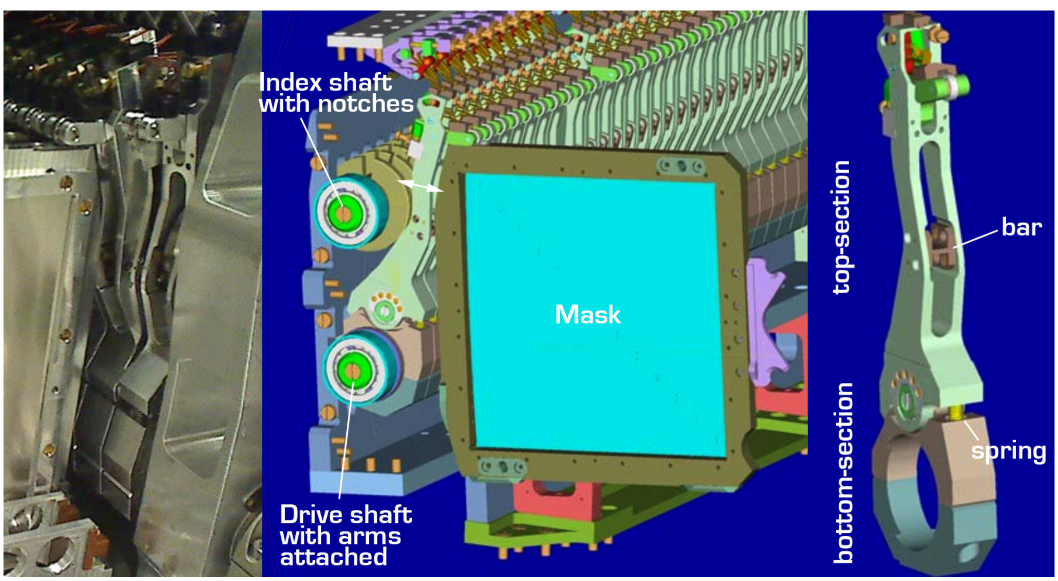

Figure 7: Left: Retainer arms in locked and unlocked position. Note the compressed and expanded springs in the bottom section. Middle: CAD overview of the retainer with drive and index shaft. Right: a single retainer arm

Radiation Shield Shutter

During a cabinet exchange an opening of roughly 30x30cm in the radiation shield of the main LUCIFER cryostat is required. This opening exposes the cold volume to a high radiation load and to stray light. Therefore, it has to be closed during normal LUCIFER operation. This is done by using a shield shutter. The shutter essentially consists of a shutter blade, a clamp system, and the drive unit. The shutter blade covers the cutting in the radiation shield. The clamps close around the two rails on which the cabinet rides, and which protrude beyond the radiation shield towards the gate valve. The drive unit is powered by a stepper motor connected to a ballscrew. The linear motion is converted into a rotation by a gear-rod / gear-wheel combination.

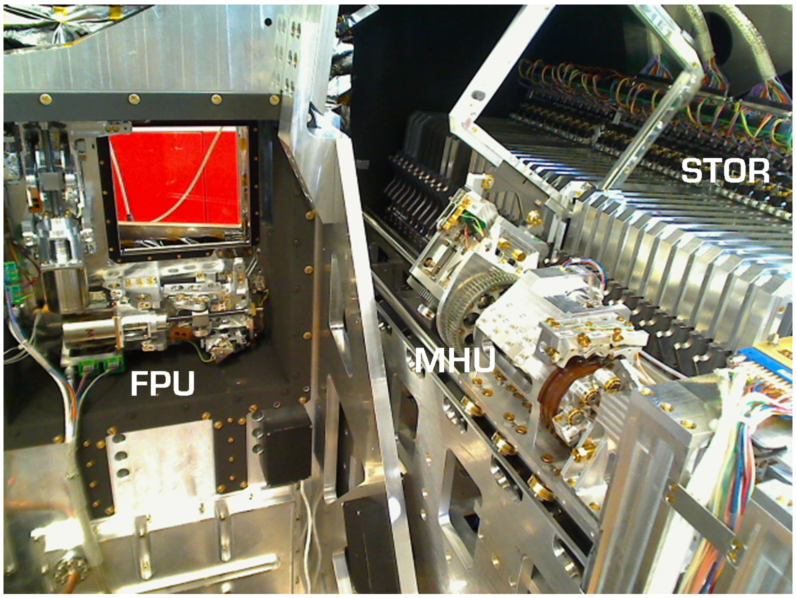

Figure 8: Arrangement of the MOS components inside the LUCIFER cryostat. In the image the MHU is taking a mask out of the cabinet for transport to the FPU. When fully integrated the space left to the MHU is occupied by the folding mirrors and collimator optics.

2.5 Mask Cabinet Exchange components

One of the outstanding features of the LUCIFER MOS is the possibility to run a complete 23 MOS-Masks cabinet exchange while preserving full cryogenic conditions within one day of daytime engineering, i.e. between two science nights. The mask cabinets are driven in and out of the LUCIFER cryostat using a spiral screw as described above. Cabinets are supplied and received by an auxiliary cryostat that attaches to the main instrument cryostat.

Auxiliary Cryostat

The auxiliary cryostats reside in a support structure of roughly 80x80x160 cm in size, resulting in a total weight of about 400kg. They attach to the Lucifer cryostat through a vacuum interface with a free diameter of 30cm. When attached they reside and are guided on rails on top a bridge-like structure which is permanently bolted to the telescope. Thereby no shearing force is applied to the vacuum interface due to the weight of the cryostat. Both the LUCIFER cryostat and the aux-cryostats are equipped with gate valves. Inside the cryostat rails and a spiral screw are mounted to drive the mask cabinets in and out (see Figure 10). Since the aux-cryostats are used only for cooldown, transport and warmup of the mask cabinets, no retainer or other storage structures are integrated into these units. We have implemented a thermal bridge that can be lowered onto the masks for faster cooldown or warmup. On top of the outer support structure an electronics rack is mounted which controls the vacuum pump system as well as the cabinet drive when a cabinet is loaded and unloaded in the lab. This makes the auxiliary cryostats completely independent. Also the gate valves are controlled from the auxiliary control electronics panel. Opening the gate valves is secured by various interlocks. During the actual transfer, the LUCIFER control electronics takes control over all movements since the motions of the

LUCIFER and the aux-cryostat cabinet drive need to be synchronized during the moment of cabinet handover between the two units.

The cryostats hold up to 30 liters of liquid nitrogen in a tank coupled to its internal structure. Cooldown takes about 24h with all masks being at LUCIFER operating temperature another 18-24h later. For rapid warmup heaters can be switched on. The cryostats are equipped with all vacuum pump equipment needed to pump the cryostats as well as the vacuum interface between the auxiliary and LUCIFER gate valve. Communication to the main instrument is done via signaling cables which the support staff at the telescope needs to connect to LUCIFER manually. Interlocks ensure that all cabling and preparation steps have been completed successfully before a transfer can be run from a dedicated software GUI.

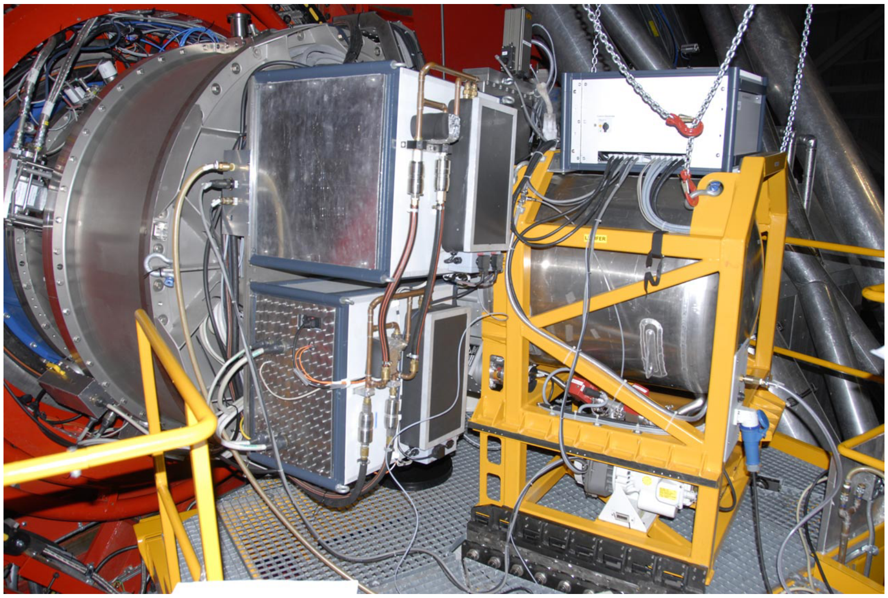

Figure 9: LUCIFER (left) with an auxiliary cryostat attached (right). The aux. cryostats rails on the bridge are also visible.

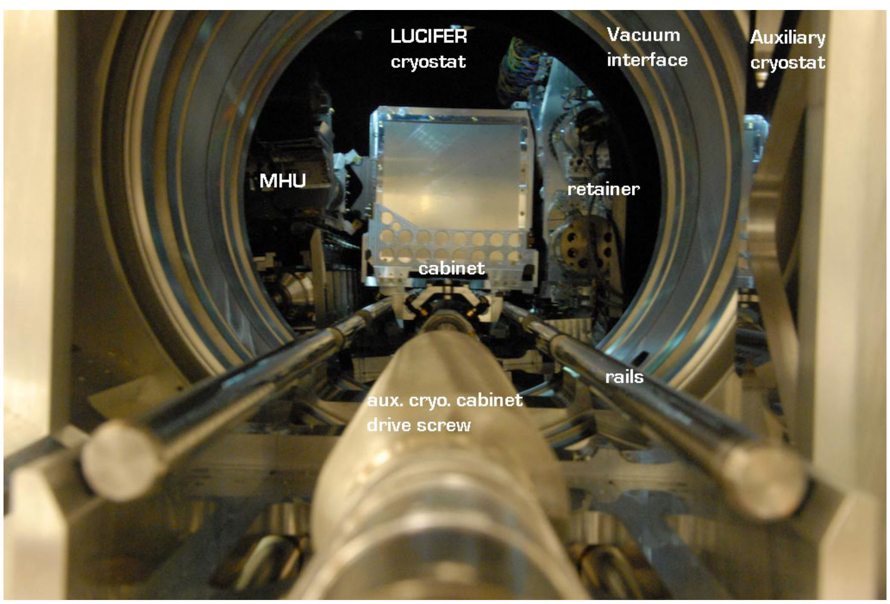

Figure 10: View along the cabinet drive from the auxiliary cryostat towards the Lucifer cryostat. During transfer the cabinet is handed over from the LUCIFER cabinet drive to the Auxiliary Cryostat Cabinet drive in a synchronous motion of the two screws.

3. OPERATION, MOTIONS AND CONTROL

3.1 Electronics

The control electronics for the MOS unit is mounted in a rack on top the main LUCIFER cryostat. Communication is done through a fiberline interface using RS232. The electronics is divided into two sections: The motor controller accepts addressed motor steps from the control software and then send them to the motor hardware. It also monitors the angular encoders and calculates the current motor position. Motor-limit-switches are hardwired to the motor controller to shut of motions when mechanical limits are reached. From the controller board signals are send to dedicated motor driver modules. The other section is the FPGA based switchbox. Signals of micro switches that are not limit switches, such as state and position indicating switches are fed into this component. It is read out by the operations software, which mainly uses its output for checking pre- and postconditions of sequences. The switchbox also does Boolean operations on various inputs needed for interlocks. In the now final version of the MOS unit, we also monitor the gravity vector and the instruments motion using an accelerometer. This is necessary for some auto debugging functions where it is helpful to know the direction of the gravity vector at the mask frame position relative to the robot.

To be able to inspect and monitor motions in more detail under cryogenic conditions we have recently added a camera and vibration monitor. The camera is monitoring the storage side of the unit as well as the robot. It is based on a commercial USB-CCD webcam and is temporarily warmed up to working temperature (80K above instruments temperature) when needed. It features LEDs to illuminate the otherwise dark cryostat. We have modified the sound input to record structure-borne sound to analyze and check mechanical vibrations on a regular basis. Constant vibration control (‘acoustic management’) however is not necessary.

3.2 Software

Running a mechanical system as complex as the LUCIFER MOS unit cannot be accomplished by executing static hard-wired movements. For example the robot arm must precisely transport the masks between the storage and the FPU for each orientation of the instrument. A correct placement of the masks can only then be guaranteed if the motion is controlled by software which adapts the motion according to changing conditions caused for example by flexure.

The Lucifer control software is a Java based multi-tier service architecture. The MOS unit service accesses two sub services for the two electronics units described above: One implements the communication with the motion control unit. It is used to issue all active motion commands, operate magnetic locks and query angular resolvers. The other service provides access to the switchbox, which reflect the status of the mechanical elements. There exist four methods to transport a mask between FPU, turnout position and storage plus additional two methods to perform a cabinet exchange. To guarantee a secure transport of the masks a state-transition model is used. Each action of the MOS unit is bundled in a sequence together with a start and end state (pre- and post-conditions). Each sequence can represent any kind of motion from a simple one motor-transition motion to a tree of complex sub-sequences. The applied state-transition model allows a save operation of the instrument at all times. In case a transition does not reach the expected end-state corrections can be applied (e.g. to reach an angle or to trigger a switch). The MOS controlling service can be directly accessed through an engineering GUI. It incorporates access to both sub-services that directly access the hardware. Furthermore the available sequences and their states can be executed and checked. To the science user and higher-ranking instrument control service the MOS Unit is completely transparent and can be operated using a simple GUI (or internal software calls respectively) which only select the mask and end-position and request the start of the motion. For convenience mask configuration (name, type, position, observation-ID) and the cabinet exchange have been implemented in separate GUIs. The cabinet exchange GUI was designed to automatically detect the current status of the attached auxiliary cryostat and guide system engineers through the delicate exchange procedure.

3.3 Interlocks

We have implemented hard and soft interlocks for functions and movements of the MOS unit components. Ballscrews are equipped with limit switches on both ends, likewise the two ends of the retainers rotating motion feature limit switches. These are hard stops that shut off the motion directly inside the motor controller. Also from the engineering panel further movement is then prohibited to prevent permanent damage to the unit.

The pre- and post-conditions every software sequence features are soft interlocks. They cannot be overridden by the normal user or the high level control software. In low level engineering mode these conditions can however be overridden for debugging purposes.

The two vacuum gate valves cannot be automatically opened or closed in any way. They need to be activated using push buttons secured by mechanical stops. Additionally certain criteria must be fulfilled before the opening pulse is led through to the valves.

3.4 Auto-recovery and Error correction

Each motion sequence has pre- and post-conditions that need to be fulfilled before or after the movement. Higher level sequences can have additional conditions. If these conditions are not met, we call motion correction sequences, depending on the high level sequence or the movement involved to automatically correct deviations from the desired condition. In the case of rotating motions for example we define a target angle as well as a tolerance ('target interval') as well as a larger interval that must be reached and from which we then call a correcting motion. Corrections are done by either commanding the same target condition ('retry') or by running specialized debug sequences. Different instrument positions (rotation and tilt) result in changing weight distribution and force vectors on the various components of the MOS unit. Therefore it can be necessary to call different correction sequences. If condition-exceptions are encountered that could be caused by a critical instrument state and moving on could result in permanent damage, the unit is stopped on a low control level. Manual inspection has then to follow. While executing a sequence or collection of sequences, the control software builds up an execution tree, which contains additional debugging information for the system engineer. E.g. the reason why a sequence was stopped is explained or the applied correction mechanism can be reproduced. The execution tree allows to pause sequences and also run step-wise in order to test new parameter sets after hardware modifications.

3.5 Motion Example

We now describe an the motion of a mask from storage to the FPU. We start out with no mask grabbed and the rotator at storage. This is the state after the instrument has been put to operation after cooldown or after a mask has been put back to the storage cabinet.

From the user panel a mask number and "FPU" as the desired end position is selected. The software calls a sequence 'Storage-to-FPU'. We internally run a couple of pre-checks to see if the unit is still ready. If small deviations are present (like that the rotation-head has moved by a fraction of a degree during motor power switch-on) we correct these to nominal positions. Now the MHU moves in translation direction to the desired mask in the cabinet. The amount of steps that is needed is calculated from the current value and an absolute position value stored in a lookup table. After moving the necessary steps to the selected mask position, we compare the translation angle with the value stored in the mask-lookup table and correct if necessary. The grabber motor holding current is then activated and the mask is grabbed. The motion stops when the nominal number of motor steps have been executed. In case we have not reached the limit switch the motion is either repeated or continued until the grabbers limit switch is reached. The grabber's strain gauges are read out to check if the mask was properly grabbed. With the retainer still closed and masks locked the index shaft is rotated to the angle corresponding to the selected mask. After selection is done, the retainers drive shaft is rotated. This moves the mask locking arm backwards, unlocking the mask and leaving all other masks still locked. Now the mask is rotated from the storage angle out of the storage cabinet and into transport position where the rotation head of the MHU is locked in place. In this configuration the MHU can move safely towards the FPU and it stops at the FPU's 'open' position.

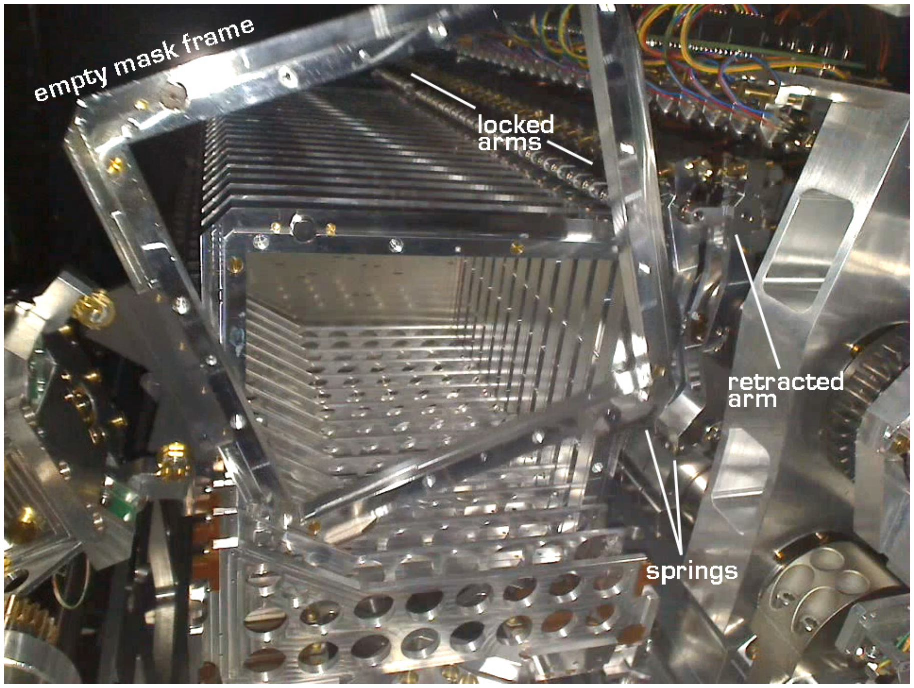

Figure 11: The MHU is taking an empty test mask frame out of the cabinet. On the right: The corresponding arm of the retainer is retracted, all others stay locked. Grabber and mask frame handle can be seen on the left.

After a pre-check, testing if the FPU is ready to receive the mask (and starting an auto correction if it is not) the MHU-rotation lock is removed and the mask is rotated into the FPU. Magnets inside the mask frame activate reed contacts that now indicate the presence of a mask inside the FPU in open position. Rotation is locked again. The MHU then moves forward in the direction of the focal plane pushing the mask on the centering pins. Once the mask is in contact with two spring loaded pads located to the left and right of each centering pin, the reed contacts indicate that the mask is in hold position and the two FPU clamps move downwards until their spring loaded tips hold down the mask. Then the MHU grabber releases the mask. Finally the FPU clamps close completely, pushing the spring-loaded pads completely into the FPU base plate. We check the reed-contacts and clamp-arm limit switches to see if the mask is in its final locked position. Upon completion the MOS subsystem signals the high level software that the motion is complete and the user can now use the mask as desired. Putting the mask back follows a very similar sequence in reverse.

REFERENCES

[1] Hofmann, R., Mandel, H., Seifert, W., Seltmann, A., Thatte, N., tomono, D. and Weisz, H., "Cryogenic MOS-unit for LUCIFER", Proc. SPIE 4841, 1295-1305 (2003)
[2] Hofmann, R.,Gemperlein, H., Grimm, B., Jütte, M., Mandel, H., Polsterer, K. and Weisz, H., "The cryogenic MOS unit for LUCIFER", Proc. SPIE 5492, 1243-1253 (2004)
[3] Seifert, W., Appenzeller, I., Baumeister, H., Bizenberger, P., Bomans, D., Dettmar, R.-J., Grimm, B., Herbst, T., Hofmann, R., Juette, M., Laun, W., Lehmitz, M., Lemke, R., Lenzen, R., Mandel, H., Polsterer, K., Rohlo□, R.-R., Schuetze, A., Seltmann, A., Thatte, N.,Weiser, P. and Xu, W., "LUCIFER: a Multi-Mode NIR Instrument for the LBT", Proc. SPIE 4841, 962-973 (2003)
[4] Seifert, W., et al., "LUCIFER1: Performance results", SPIE Paper No. 7735-292 (2010)
[5] Ageorges, N., et al., "LUCIFER1 commissioning at the LBT", SPIE Paper No. 7735-56 (2010)