MELT - An optomechanical emulation testbench for ELT wavefront control and phasing strategy

T. Pfrommer*[a], S. Lewis[a], J. Kosmalski[a], P. La Penna[a], C. Frank[a], I. Guidolin, S. Leveque[a], A.-L. Chaffot[a], H. Bonnet[a], N. Kornweibel[a], J. Spyromilio[a]
[a]European Southern Observatory, Karl-Schwarzschild Strasse 2, 85748 Garching, Germany

ABSTRACT

We present an optomechanical test bench setup (MELT) for testing and validating key functionalities to be used on the Extremely Large Telescope (ELT) during the periods of system verification, wavefront control commissioning, through the handover to science, up to regular diagnostic, monitoring, and validation tasks during operations.
The main objectives of MELT are to deploy and validate the telescope control system, to deploy and validate wavefront control algorithms for commissioning and operations, as well as to produce and validate key requirements for the phasing and diagnostic station (PDS) of the ELT.
The purpose of MELT is to deploy optomechanical key components such as a segmented primary mirror, a secondary mirror on a hexapod, an adaptive fourth mirror, and a fast tip/tilt mirror together with their control interfaces that emulate the real telescope optomechanical conditions. The telescope control system, deployed on MELT can test control schemes with the active mounts emulating the real ELT optomechanical control interfaces.
The presented optomechanical setup uses the Active Segmented Mirror (ASM) with its piezo-driven 61 segments and a diameter of 15 cm. It was designed, built, and used on sky during the Active Phasing Experiment (APE).
Several beam paths after the telescope optical train on MELT are conditioned and guided to wavefront sensors and cameras, sensitive to wavelength bands in the visible and infrared to emulate wavefront commissioning and phasing tasks. This optical path resembles part of the phasing and diagnostics station (PDS) of the ELT, which is used to acquire the first star photons through the ELT and to learn the usage and control of all the ELT optomechanics. The PDS will be developed, designed, and built in-house at ESO. MELT helps its design by providing a detailed test setup for defining and deploying system engineering tasks, such as detailed functional analysis, definition of tasks to be carried out, and technical requirements, as well as operational commissioning aspects.
The bench test facility MELT will in the end help us to be as much as possible prepared when the telescope sends the first star light through the optical train to be able to tackle the unforeseeable problems and not be caught up with the foreseeable ones.

Keywords: ELT, test bench, segmented mirror, phasing

1. INTRODUCTION

The miniscule ELT (MELT) is an optomechanical test bench with the aim to fulfil its objectives, namely, to provide the means to develop, deploy, and test wavefront control strategies, provide the hardware interfaces that emulate the ones from the ELT for the telescope control system to be used as validation tool, as well as provide the necessary input for the development of the phasing and diagnostic station. The fact that it does not only exist virtually but as real hardware will help to check in reality on detectors with real error budgets how wavefront control can work on the ELT. For example, the, the ELT main axis control is emulated with a moveable diffraction-limited source that emits white light from the visible up to the K band through a turbulence generator. Another example is a single conjugate adaptive optics (SCAO) Shack Hartmann (SH) wavefront sensor (WFS), which is used in closed loop with an ELT real time computer and M4 to test and validate offloading scenarios to M5 and the main axis. This SCAO functionality is crucial to test the influence of adaptive optics on M1 phasing performance using the baseline SH high order WFS, but also M4 phasing issues with its petals, and scalloping can be tested. The bench also allows to test different phasing concepts that will support the SH baseline.

*tpfromme@eso.org; phone +49 89 3200-6663; www.eso.org

Most optical systems are designed to minimise aberrations and misalignments. In MELT, we are doing the opposite and this has been an interesting challenge for the optical and mechanical designers such that the deliberate errors in MELT have the same properties as those the telescope will exhibit due to perturbations such as gravity and temperature as well as AIV tolerances. Purposely misalignable optics will emulate the optically imperfect telescope. Pupil rotation and derotation optomechanics create a realistic beam (in)stability that needs active pupil stabilization used to meet the stringent pupil registration requirements for SH phasing strategies of the ELT.

2. MELT OBJECTIVES, DESIGN APPROACH, AND GENERAL SET-UP

As mentioned previously, one of the main objectives for MELT is to establish and define key requirements for the phasing and diagnostic station of the ELT. We performed in this framework a functional analysis and analysed user requirements, which apply in big parts also to MELT. MELT and the PDS are hence interlinked. We outline in the following the systems engineering approach, which has been established for MELT with a very close link to the PDS.

The PDS will be used to characterize, verify, and validate telescope performances at the Coudé focus position on the Nasmyth platform inside the pre-focal station (PFS) of the ELT[1]. It is fed by M6C, the fold mirror in the PFS, which delivers a 1 arcmin field of view vertically down to the PDS, or the Coudé train. It will be an integral part of the telescope, capable of providing an instrument-independent diagnostic method, as well as a learning and verification tool during AIV and wavefront commissioning[2] for most telescope functions within the maximum field of view of 1 arcmin on-axis, including single-conjugate adaptive optics and laser guide star diagnostics.

For the PDS, it is foreseen to keep the system responsibility in-house and the ESO-team will lead all phases through design, manufacturing, integration, and testing.

2.1 MELT and PDS main functionalities

To derive user requirements and perform the mentioned functional analysis for the PDS, MELT has been used as a precursor to start this process and define the most relevant functions. These general functions of MELT are listed in the following, having in mind the later-on used functionality in the ELT. For the PDS, inputs from AIV, PFS, and systems engineering, apart from the obvious users of MELT, namely telescope central control system, wavefront control performance and validation[2], and the PDS, are considered.

- Sensor arm functionality for on-axis performance before the PFS takes over this functionality after the field performance of the ELT is verified
    - VIS imager with tip/tilt guider requirements and a 12 arcsec (MELT)/ 1 arcmin (PDS) field of view and seeing limited pixel sampling.
    - SCAO Shack-Hartmann (SH) WFS in the visible that works on closed loop with the adaptive M4 via a dedicated RTC (MELT and PDS), but could also be used during the first steps of wavefront commissioning for stacking and segment capture tasks. Interaction matrix validation can be performed in conjunction with the NIR focal plane imager
- Near infrared (NIR) focal and pupil plane imaging (in MELT, exchangeable optics to one detector, in the PDS 2 NIR detectors and dedicated optical paths) in J, H, and K band up to 2.1 microns
    - Focal plane imaging with diffraction limited sampling capabilities not only for Strehl performance validation and focal plane verification tasks, but also for fringe detection during segment capture and optical axis definition at the very start of wavefront commissioning
    - Pupil plane imaging for M1 phasing support of the ELT baseline Shack-Hartmann phasing strategy, using a Zernike wavefront sensor-type strategy with a phase mask, as well as for verifying telescope performance in the pupil plane.
- High-order Shack-Hartmann visible phasing WFS
    - For the moment, 19 subapertures (SA) per segment with overlapping SA to adjacent segments demand high pupil stability and pupil shape control to a relative accuracy of 10^{-4}. This sensor will also be used during the segment capture, stacking, and shape control. For MELT with its 61 segments on M1 a 512 x 512-pixel visible detector is enough. For the PDS, this demands for at least a 4k x 4k detector, which in addition shall be read out at full frame rates of several tens of Hz.

- M4 petal phasing detector
  - On MELT, the deformable mirror is not segmented, but a static phase screen is foreseen to be installed and emulate fixed phase steps. In the ELT, M4 consists of 6 equal pie-shaped petals, whose piston steps need to be monitored by the PDS and, if needed, corrected.
  - To match the instrument WFS type for NGS NIR tip/tilt detection, a pyramid WFS could be foreseen for this task, ideally folded into either the NIR focal or pupil plane imaging path, with an extended purpose and not limited to the mentioned petal phasing task.

2.2 Design strategy

The design process starts with the MELT objectives

- Deploy and validate the Central Control System;
- Develop and validate wavefront control for commissioning and operations;
- Get and validate requirements for the PDS;

The objectives are further broken down into tasks, which in turn consist of use cases and operational scenarios. For MELT, the main design driver is, what it takes to bring the telescope at the end of the AIV phase to delivering diffraction-limited performance.

Table 1: A non-exclusive list of identified tasks and the relevance to MELT and/or the PDS is given.

Tasks	MELT	PDS
Support in populating look-up tables during initial telescope mirror alignment (main axis actuators, M1 PACTs, M2 RBM, M3 RBM, M4 RBM, M5 RBM)	(✓)	✓
M1 active control functions characterization (LOO characterization)	(✓)	✓
M1 phasing measurement (includes segment capture, stacking, coherenceing, …)	✓	✓
Blind slew performance characterization	✕	✓
M1 scalloping measurement	✓	✓
M2 active control functions characterization	✓	✓
M3 active control functions characterization	✕	✓
M4 response (static and dynamic)	✓	✓
M4 phasing	✓	✓
M5 response (static and dynamic)	✓	✓
Stroke management and offloading schemes (M4, M5, main axis)	✓	✓
SCAO + control handover (cascade, sequential)	✓	✓
SCAO performance (characterization of M4-5 latency, pupil motion, CCS I/F, ...)	✓	✓
Verification of field/pupil stabilization, including low order AO for wind correction	(✓)	✓
Seeing-limited performance plus acquisition sequence (pointing, focus correction)	(✓)	✓
Offsetting/nodding	(✓)	✓
Non-sidereal tracking performance	✕	✓
LGS pointing and field/pupil tracking validation	✕	✓
LGS performance characterization (jitter, instantaneous PSF, return flux at Nasmyth, elongation, LGS scattering, …)	✕	✓

In this context, critical areas are identified and detailed analysis with system performance in mind is carried out[3]. This leads to the relevant ICDs and technical specifications, which, for the PDS, also incorporates results from MELT.

2.3 General setup of MELT

MELT is a test-bench on an optical table, which is the continuation of the active phasing experiment (APE)[4], carried out in the framework of ELT phase A risk mitigation work 10 years ago at ESO. During this experiment, 4 different WFSs have been tested about their capabilities to phase an in-house developed and built segmented mirror (active segmented mirror, ASM, see Figure 1) consisting of 61 segments, each driven by 3 piezos to control piston, tip, and tilt with a free mechanical stroke of 15 um for wavefront control. Another 15um is used to compensate for integration tolerances and an internal metrology device, based on multiline interferometry, is used to check the phasing capabilities of the different wavefront sensors.

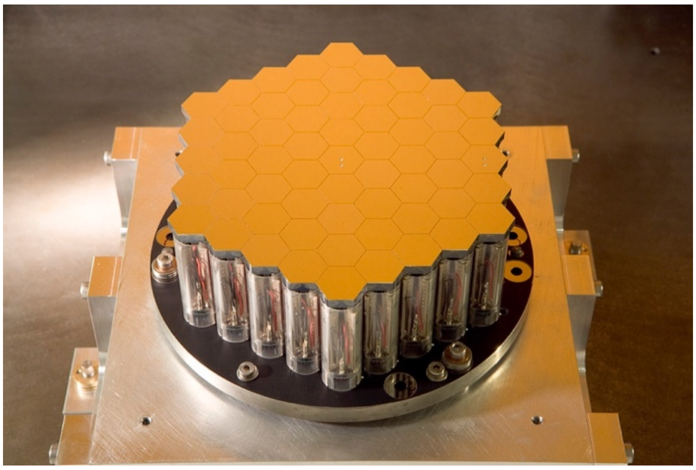

Figure 1: The active segmented mirror, readily integrated during the active phasing experiment. Picture courtesy of the APE team.

The experiment was done in the lab, and on one of the VLT Nasmyth foci to get on-sky performance data and comparison to lab results, where the control over vibration levels and turbulence is easier, but less realistic. For MELT, this optomechanical setup needed to be upgraded, yet keeping the segmented mirror and the turbulence generator. IR capabilities are added to the bench, and the telescope emulation capabilities are substantially augmented by installing optics that emulate M2 of the ELT on a hexapod, the intermediate focus, an adaptive deformable mirror, the fast tip/tilt mirror, and a pupil rotator to put realistic pupil instabilities on the bench. The same actuator is used to compensate in some wavefront control scenarios the pupil motion and actively runs a closed loop. Other scenarios deal with the pupil rotation by fast detector read outs and software derotation. In front of the telescope path the MAPS turbulence generator is reused from APE, as is the calibration source directly after MAPS. Due to the enhanced wavelength range and field of view requirements of MELT, most optics needed replacement and a new optical and with it optomechanical design has been carried out. To test efficient offloading schemes before going to the telescope, the source in front of the turbulence generator, which consists of a bright fiber-coupled broadband source in the wavelength range from 400nm to 1700nm (MELT), is diffraction limited at the fiber output and mounted on a motorized X-Y stage to emulate the telescope main axis.

2.4 The telescope emulator

The total unobstructed field of view of MELT is +/- 4 mm, or, with its plate scale of 662 um/arcsec, +/-6 arcsec (on sky). The motorized stage can move the source further within the range of +/-10mm on both axes, which is used in case the M2 lens assembly (the M2 powered optics of the ELT is emulated as a lens assembly in MELT) on the hexapod is purposely misaligned to produce enough coma and astigmatism to sense scalloping effects on the M1 segmented mirror. A spider mask in a pupil plane between lens groups 1 and 2 can be automatically moved into the beam to mask light from certain areas on the ASM, hence realistically produce islands of segments by shading in the pupil the geometrically scaled areas, so that the wavefront control strategy can be adjusted to this complication before going to the real ELT. Only 3 spider arms are used in MELT (compared to the 6 spider arms of the ELT) to still have enough usable fully illuminated segments on the 61-segment ASM. After the beam passed the turbulence generator, the spider mask, the ASM, and the M2 lens assembly, it goes through the intermediate focus, and subsequently bounces off the deformable mirror with 277 actuators, before the fast tip/tilt mirror, emulating M5 is passed (see Figure 2).

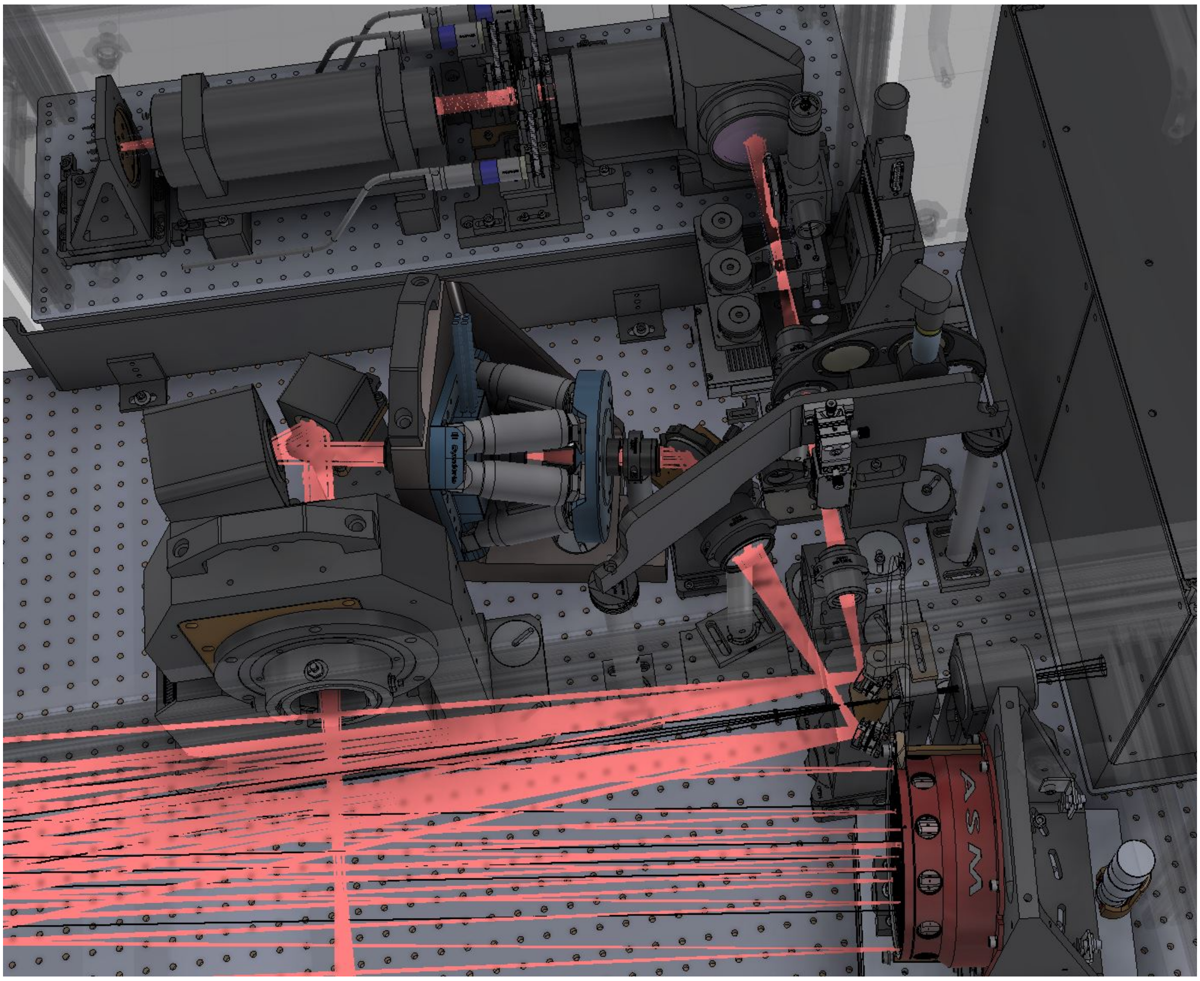

Figure 2: The telescope emulator optomechanical design and optical beam path. The beam enters, after passing through the turbulence generator (horizontally on the top), on the top right, passes through a filter wheel and spider mask, bounces subsequently off a small mirror, gets collimated by an off-axis parabola, used in double pass, and in between hits the ASM in the lower right of the picture. After hitting a second small folding mirror, the beam enters the M2 lens assembly on the horizontally mounted hexapod before it goes through the adaptive mirror and tip/tilt mirror. At the end, it passes the rotator/derotator unit, hosting a K-mirror prism design.

The pupil rotator afterwards finishes the path through the telescope emulator, and the diagnostic path starts. As mentioned in the beginning of the document, one other main objective of MELT is to provide the central control system of the ELT (CCS) with necessary hardware that it can be interfaced with and validate its functionalities. Although MELT does not have – naturally – the actual ELT hardware, interface boxes for each unit will emulate those so that the CCS interfaces with what looks like the actual ELT hardware. As such, MELT will use the internal metrology, developed during APE, to diagnose the piston/tip/tilt status of each of the 61 segments separately to the diagnostics path, and broadcast the result to the network in a transposed way that the CCS receives values to be interpreted as edge sensor data. Due to questions about the reliability of the internal metrology and its complicated design, done for APE, a secondary way of emulating segment edge sensors is to use the direct feedback from the segment piezo actuators and transpose them to edge sensor data.

2.5 The diagnostic unit the resembles functions of the PDS

Section 2.1 already described the main functions of the MELT diagnostic path. Figure **3** depicts the bench layout and labels its main components.

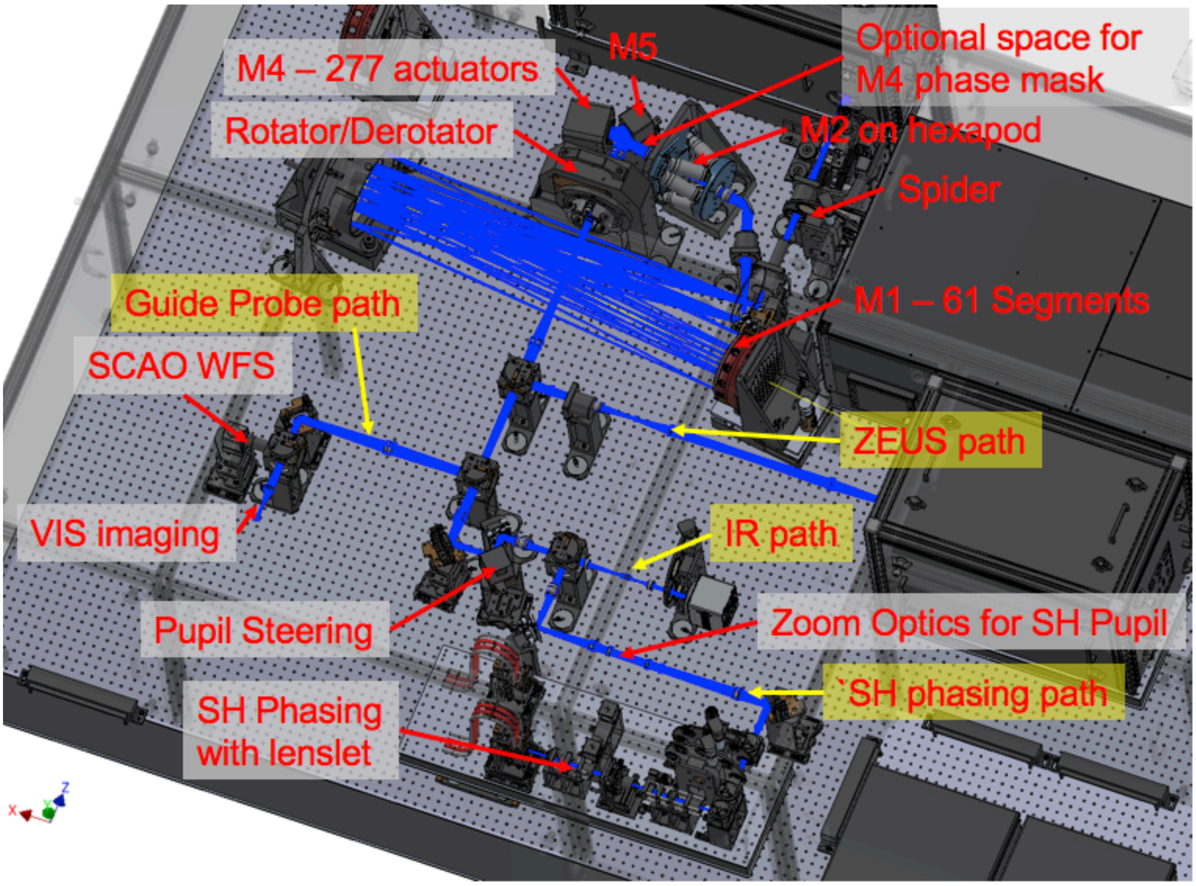

Figure 3: MELT bench layout with labelled components.

A first beam splitter (after the rotator) sends some light to the guest path. It is labelled "ZEUS path" in Figure **3**, and consists for the moment of a wavefront sensor, used in a PhD thesis. A second beam splitter opens the path to the sensor arm, labelled "Guide Probe Path", where the SCAO SH WFS and the VIS imager/tip-tilt guider is located. An intermediate focus provides a possible location for a calibration source for the WFS. The straight through path through beam splitters 1 and 2 passes through a fast steering mirror, that is used to stabilize the pupil, before a third beam splitter separates the "IR path" from the "SH phasing path". The IR path allows, via automatic exchange of a focusing lens with a phase mask for M1 phasing functions, to flip between pupil imaging and focal plane imaging mode. The SH phasing path contains 3-stage zoom optics. In MELT, this is manually adjusted, but in the PDS, this will be automated, and maybe cylinder lenses for automated astigmatism control will also be added. The pupil stability requirements on the ELT of 10^{-4} is a very stringent requirement and will need close monitoring during the PDS design process. This includes not only the dynamics of pupil zoom and tip/tilt stability, but also pupil distortion.

3. THE OPTOMECHANICAL DESIGN

With the understanding of the general functionalities and requirements, a block diagram was developed that contains all necessary ingredients to start the optomechanical design process. Figure 4 shows the final version. This is also the starting point for the control design to identify the interfaces to the relevant hardware on the bench.

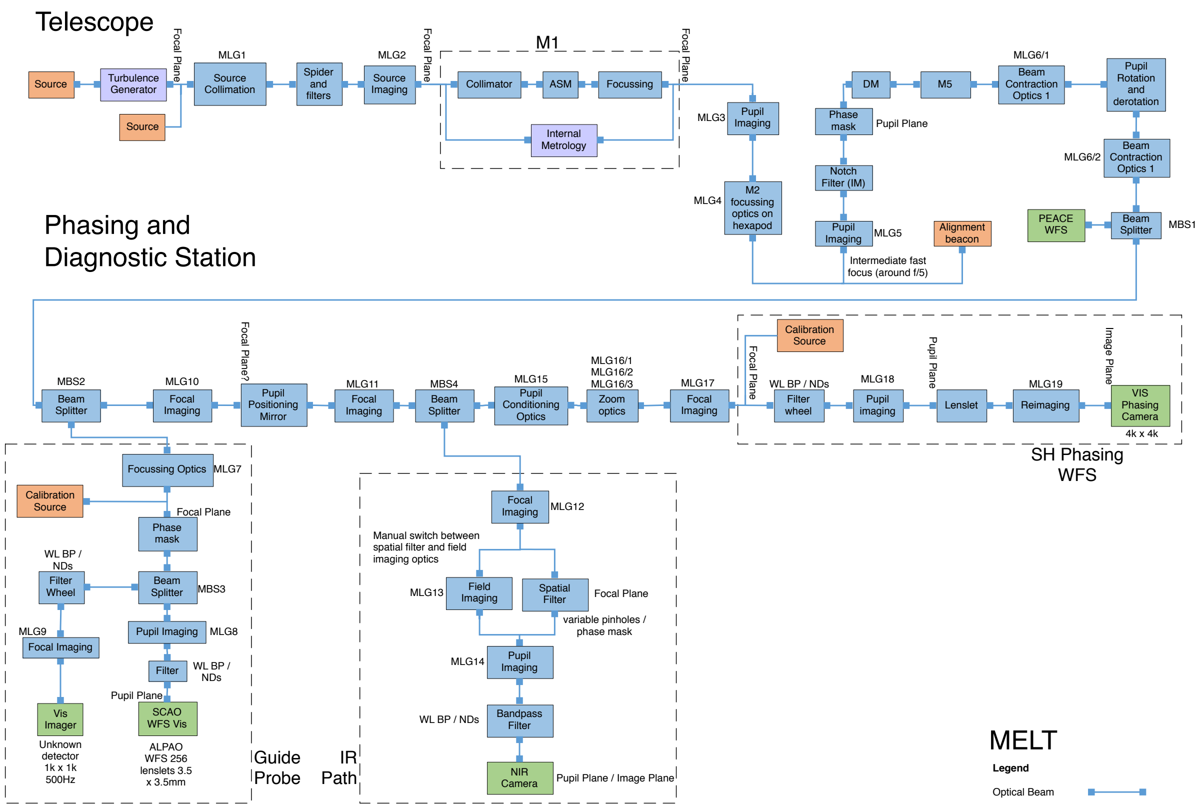

Figure 4: The MELT block diagram showing the beam path from the source, via the telescope emulator to the diagnostic unit with its several beam paths for different detectors.

3.1 Relevant hardware of MELT with their requirements

Source

The source shall emit light in the wavelength range from 500 to 1700nm, of which the bands 500-800nm, 900-1200nm, 1400-1700nm are the important regions. It must be an incoherent light source, and it shall deliver at the entrance to the turbulence generator a diffraction limited point source. As will be discussed in Section 3.2, with the f/12.36 beam, at 1.55um, diffraction limited performance is given with a source of radius 19.2um. At the lower wavelength end, the diffraction limited radius is 17um. A fiber with 25um core is hence well suited. To fiber-couple an incoherent light source, which is usually produced in an electric arc, into a fiber with such a small core is not efficient. We found a bright incoherent white light source, which is based on plasma radiation generated by an internal laser (LDLS / EQ-99-FC from Energetiq). The small extent of the plasma helps to efficiently couple the light in a small fiber and enough intensity is available on the MELT bench. Signal to noise considerations have been performed using the existing detectors. The resulting integrated light power is given in Table 2.

Table 2: Integrated power levels just after MAPS at the beginning of the MELT bench optical train in the wavelength ranges of interest.

Wavelength range [nm]	Integrated power level [uW]
500-800	15
900-1200	14
1400-1700	0.6

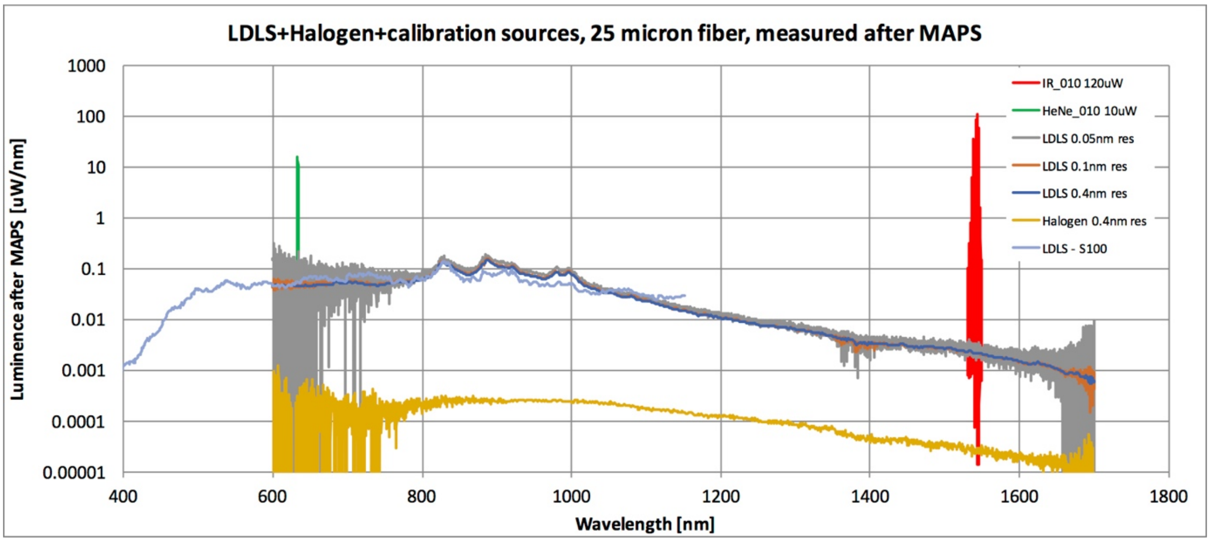

Figure 5: Laser driven light source (EQ-99) luminescence spectrum through a 25um multimode fiber, which feeds light to the MELT experiment, measured just after MAPS at the bench entrance. It is recorded with 3 different resolutions in the spectrometer for consistency check (grey, blue, orange). For comparison, a standard halogen source has been recorded and shows luminescence levels 2 decades lower (yellow). For intensity calibrations, a HeNe laser in the visible (green curve) and an IR laser at 1550nm (red curve) were used. Due to the limited wavelength range in the visible of the high-resolution spectrometer (ANDO AQ6317B Optical Spectral Analyzer), a non-calibrated visible S100 spectrometer has been used to verify the luminescence level below 600nm (light blue).

To emulate the ELT main axis, the fiber exit is mounted on an X-Y automatic stage, allowing to move the source in the field of +-6 arcsec (unvignetted).

M2

The optical design of the M2 emulator is using an assembly of 2 lens groups to reproduce M2 fuctionality, and to be able to generate known and controlled aberrations of at least 4 um rms wavefront error astigmatism and/or 4 um rms wavefront error coma. Lens group MLG4/1 is hereby fixed and MLG4/2, separated by 5 mm, is mounted on a horizontally mounted hexapod (Bora from Symetrie). These large aberrations are needed to be able to detect scalloping effects on M1. By moving the hexapod table on axis, focus errors can be introduced, too. After MLG4/2, the intermediate focus is positioned at f/4.18. The chosen mechanical design allows to safely operate the hexapod without risk of damaging the 2 lens groups MLGs 4/1 and 4/2.

M4

After the hexapod assembly and a pupil imaging lens group, the deformable mirror of MELT is located. It is an ALPAO 277 actuator deformable mirror with a clear aperture of 24.5 mm. It's coating is OK for the MELT wavelength range. Just before, the possibility of introducing a static phase mask, emulating petal piston errors on M4 can be put manually into the beam. Alignment means to match the spider and segment geometry are foreseen. No automatic XYZ stage is foreseen for this part, although the real M4 in the ELT is mounted on a hexapod. The MELT beam diameter is 22.3 mm, and the required maximum pupil blur is 1 to 1% of the pupil for the full wavelength range. The design offers 20 um on axis, 120/80 um in the field, which compares to 0.1%, 0.5%, 0.36% of the pupil, respectively. In the final control strategy of MELT, this mirror will be controlled by the real-time controller of the ELT after its development. Until then, the loop is closed with the WFS via the ALPAO computer.

Sensor arm

At the ELT at start of wavefront control commissioning, after blind slewing in the preset sequence, and the segments have been captured, the telescope will first try to guide on-axis. This functionality is represented by the sensor arm in MELT, which works in the visible, and comprises of a fast tip/tilt imager, which also has a seeing limited sampled 1 arcmin field of view, and the SCAO SH high order wavefront sensor. A fast focus in the beam path provides calibration means, which are provided automatically. For MELT, the SCAO SH WFS is the existing ALPAO 256 x 256 pixel WFS with 207um lenslets, 16 x 16 subapertures on a 3.3 x 3.3 mm pupil. The beam requirements are 10% pupil blur on each subaperture maximum on axis, and 20% in the field. The optical design achieves 3.8%/19.3%/15.9% of subaperture, respectively. The WFE is listed in Table **3**:

Table 3: SCAO SH WFS optical beam quality WFE on axis and in the field.

WL [um]	WFE [rms nm] On axis	WFE [rms nm] field
0.5	80	120
0.6	88	215
0.7	28	126
0.8	136	50

The visible imager (fast tip/tilt guider) has not yet been decided. In view of the PDS, the team thinks of purchasing an off-the-shelf model and test it on the bench. Its requirements are to image 1 arcmin field, run on small 128 x 128 window at least with 500 Hz. New scientific CMOS detector developments have shown that those devices are candidates for such a 1k x 1k imager. The optical beam quality was required to deliver 80% encircled energy. The achieved WFE and beam quality is given in Table 4.

Table 4: VIS imager (tip/tilt guider) optical beam quality WFE on axis and in the field, as well as spotsize at ensquared energy level 80%.

WL [um]	WFE [rms nm] On axis	WFE [rms nm] field	Ensquared energy 80 on axis [um]
0.5	180	180	96 x 96
0.6	103	360	42 x 42
0.7	80	300	34 x 34
0.8	150	240	50 x 50

NIR path

Before entering the IR path, the beam passes by the pupil stabilization tip/tilt mirror. This is necessary for the stringent pupil stability requirements in the SH phasing path. One idea is to use the IR pupil imaging mode to sense the pupil motion and subsequently command the pupil stabilization mirror. In this mode, different phasing strategies can also be applied, such as the Zernike wavefront sensor type, where the beam is analysed in the pupil after passing by a phase mask with an optical beam retardence difference between the inner seeing disc scale diameter recess, and the outer area of the phase mask. While modulating different segment families, fringe detection at the segment edges, when they are in phase can be observed. This requires the IR detector to be of sufficiently large size, yet provide fast readout capabilities on the full frame. On MELT, we use a laboratory IR camera with 240 x 320 pixels. This is sufficient for the moment on MELT, but further upgrades might be necessary. Certainly, in view of the PDS, where MELT could be used as test bench, as well as check for the CCS to interface already with the real ELT hardware. This fact also required us to install an automatic mount that swaps the phase mask with an imaging lens, that transforms the pupil imaging mode into a field imaging mode. In this mode, the requirements are that the pixel scale shall be 4mas/px. This is necessary during the coherencing phase at the beginning to find the optical axis of the ELT. Large segment baselines lead to small fringe patterns to be resolved. In addition, this IR imager will be used to validate the diffraction limited performance of the telescope and 4mas pixels provide a good sampling. For the PDS, however, this means that a large detector will be needed, and to have the required field of view of 8 arcsec squared, a 2k x 2k NIR detector for the J, H, and K band is needed. For MELT, however, this is not foreseen. The MELT pixel size is 9mas/px, which is achieved via an incoming f/60 beam. The MELT beam quality for the NIR focal plane imager is listed in Table 5.

Table 5: IR focal plane imaging mode – optical beam quality WFE on axis, as well as spotsize at ensquared energy level 80%.

WL [um]	WFE [rms nm] On axis	Ensquared energy 80 on axis [um]
1.4	117	260 x 260

1.5	114	280 x 280
1.6	128	320 x 320
1.7	175	360 x 360

The NIR pupil imager has the requirement on the incoming beam to have a pupil blur smaller than 1% of the pupil in H-Band (20cm in ELT M1 space). The optical design shows an on-axis pupil blur of 0.044% of pupil (3um). In the 1 arcsec MELT field of view, the blur is 0.4%/0.6% of the pupil. The MELT beam quality for the NIR pupil plane imager is listed in Table **6**.

Table 6: IR pupil plane imaging mode – optical beam quality WFE on axis.

WL [um]	WFE [rms nm] On axis
1.4	96
1.5	100
1.6	111
1.7	143

SH phasing path

This path reuses the entire SH wavefront sensor of APE, called SHAPS. Additional zoom optics have been added in front of it to adjust and properly align the pupil size to the lenslet array. In MELT this is done manually, but on the PDS, as already previously mentioned, this will be an automated closed loop device. In SHAPS, an automated calibration source is located, as well as a filter wheel and reimaging optics for the lenslet. Currently, 19 subapertures are used for each segment, including cylindrically shaped lenses over segment edges. It is foreseen, in the course of the MELT usage during the wavefront control development, to make this lenslet exchangeable to test different strategies. The detector in SHAPS is a TCCD from the VLT program, with 512 x 512 pixels. However, its limitation lies in the fact that its frame rate is slow and non-syncable. In the framework for the PDS we have identified a potential COTS item, a 4k x 4k sCMOS device that can deliver full frame rates of 24 Hz, which is in the ballpark of the needs for such a SH phasing sensor. The 4k detector size is just enough for the PDS.
In MELT, this sensor works in the visible and the beam delivers a focal ratio of 12.3 at the entrance of SHAPS. On the lenslet array, the beam quality is listed in Table **7** and the pupil blur is 14um on the 8.25mm pupil diameter (0.17% of pupil). The entire M1 will be visible on the SHAPS detector.

Table 7: SH phasing path on lenslet – optical beam quality WFE on axis.

WL [um]	WFE [rms nm] On axis
0.5	122
0.6	176
0.7	200
0.8	300
0.9	470

3.2 Optical design

Fulfilling the wavefront error requirements of MELT (see Section 3.1) was challenging in the entire wavelength range from 500nm to 1700nm. Figure 6 shows the final design.

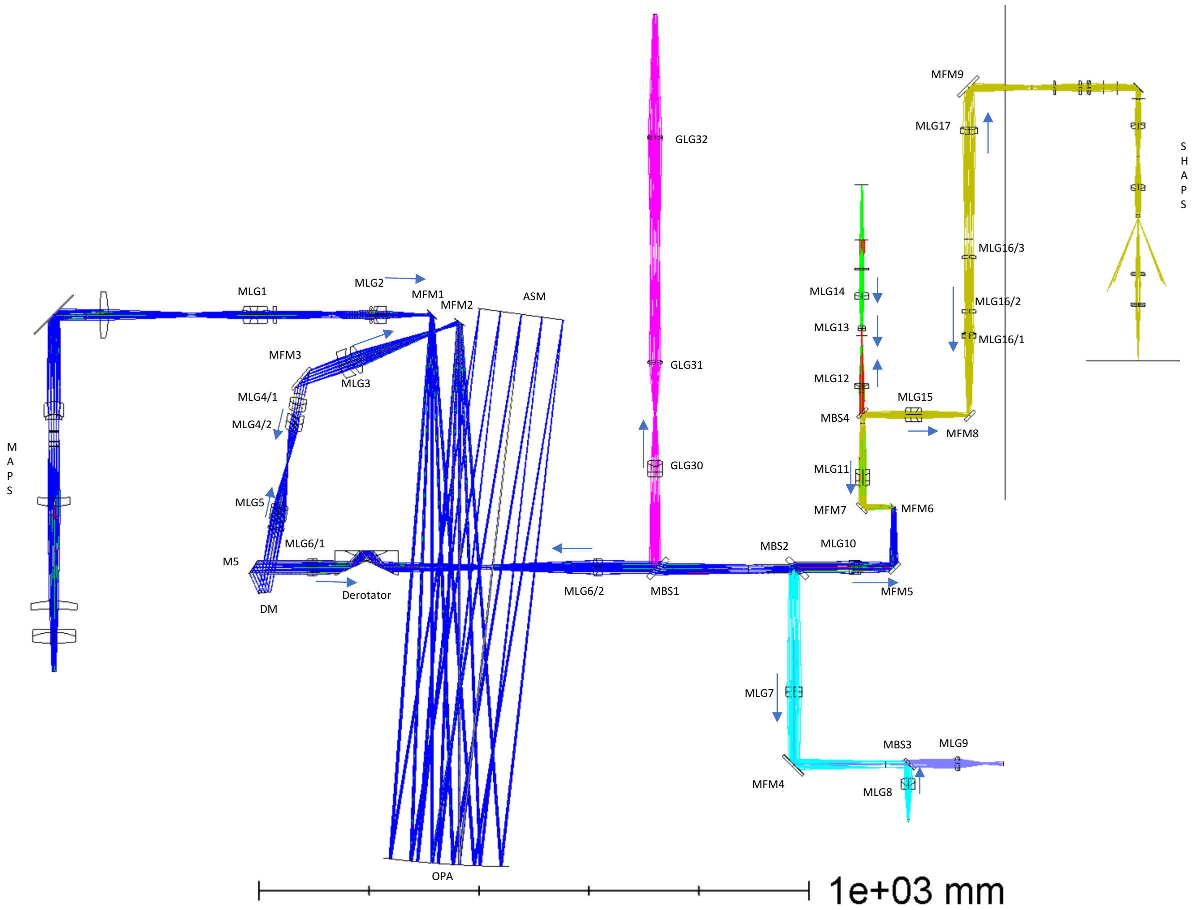

Figure 6: The MELT optical design. The blue part resembles the turbulence generator and telescope emulator. The guest (ZEUS) path is shown in pink, cyan shows the sensor arm to the WFS, while the violet part goes to the VIS imager (tip/tilt guider), the infrared path is shown in red (pupil imaging) and green (field imaging), and yellow ochre is chosen for the SH phasing path.

The general idea is to purchase mostly 30mm diameter custom made lenses some doublets or triplets, and condition the beam for the different requirements along the way. The lenses are hold in Thorlabs barrels, which are easy to interface and deliver the required stability and handling means.

MELT starts with a focal ratio of f/12.36 through the turbulence generator, who cuts the f/5 (NA0.1) beam from the fiber, and with its 1-to-1o imaging lens, this beam is transferred into the MELT telescope emulator. MLG1 forms a pupil image of 10.8 mm diameter for the optionally entered spider mask. MLG2 conditions the beam for the off-axis parabola (in double pass) / segmented mirror assembly pass, and MLG3, together with the M2 assembly (MLG 4/1 and 4/2) forms the intermediate focus with focal ratio f/4.18. An optional calibration fiber could be inserted, using the hexapod motion. MLG5 forms subsequently a pupil on the deformable mirror M4. Its on-axis pupil blur is 0.09%(VIS)/0.013%(NIR) of the pupil. In the field, it is 0.54%/0.36% in the visible on a 10 arcsec field, and in the NIR, on a 2 arcsec field it is 0.135%. The field stabilization mirror M5 is passed before MLG6/1 conditions the beam for the derotator. Together with MLG6/2 the beam is compressed for the following diagnostic paths. The non-accessible focal plane in between has a focal ratio of f/13.6. The optics that now follow on the diagnostic paths have already explained through the respective functions and the respective wavefront errors and beam quality was discussed in Section 3.1.

3.3 Mechanical design

The mechanical design is kept simple. Lenses are mostly put on interface plates with the optical table, and posts with lens barrel holders (see Figure **7**). A configuration control document has been established and is updated when more details are available.

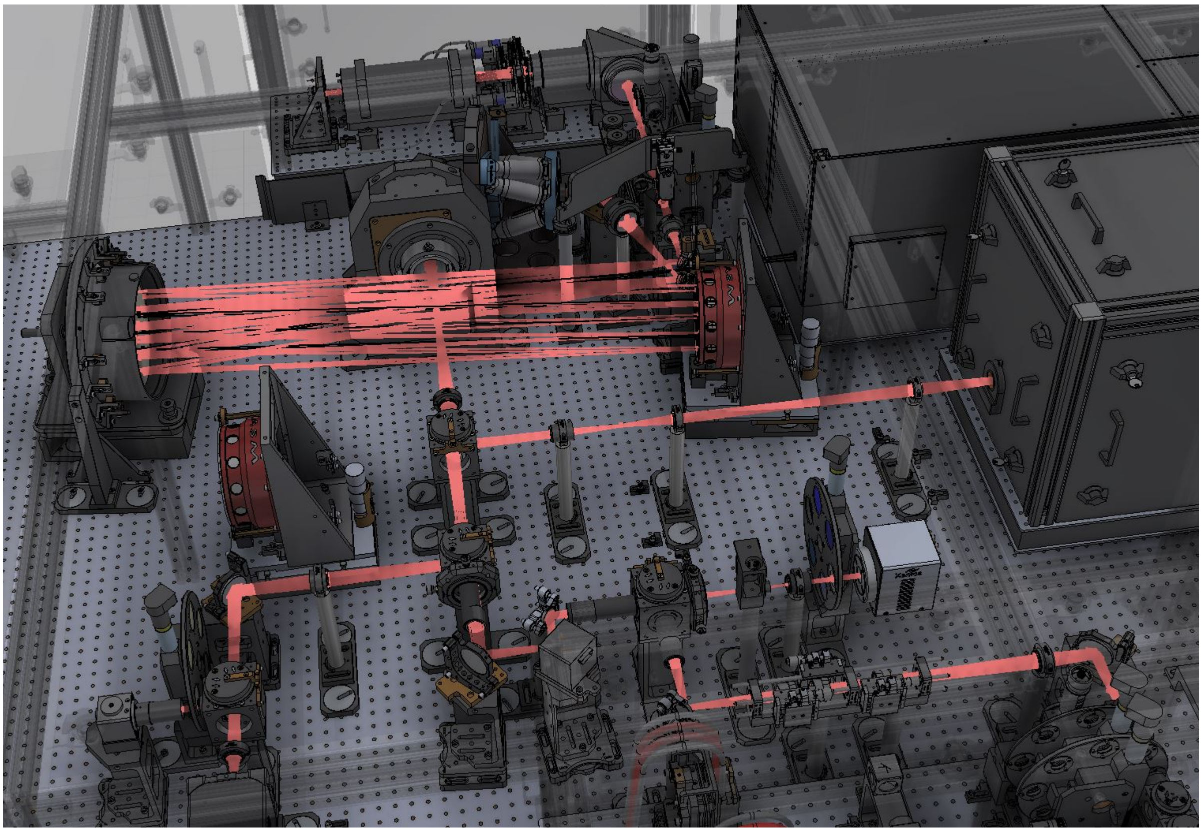

Figure 7: The mechanical design and the optical beam path is shown for the entire MELT bench.

In areas where space is limited, or where more demanding adjustment possibilities are needed, more sophisticated solutions are developed. For example, the automated spider mask mechanism had to be put on a bridge mount due to accessibility requirements to other components on the bench (see upper right beam path in Figure **7** and in Figure 8). Two lens groups (MLG5 on the bottom side of the hexapod, MLG6/1 on the entrance side of the rotator housing) are mounted horizontally due to the lack of space towards the optical table. Interfaces are provided on all relevant locations to ease the alignment process and the strategy for this phase has already started to be discussed and clarified.

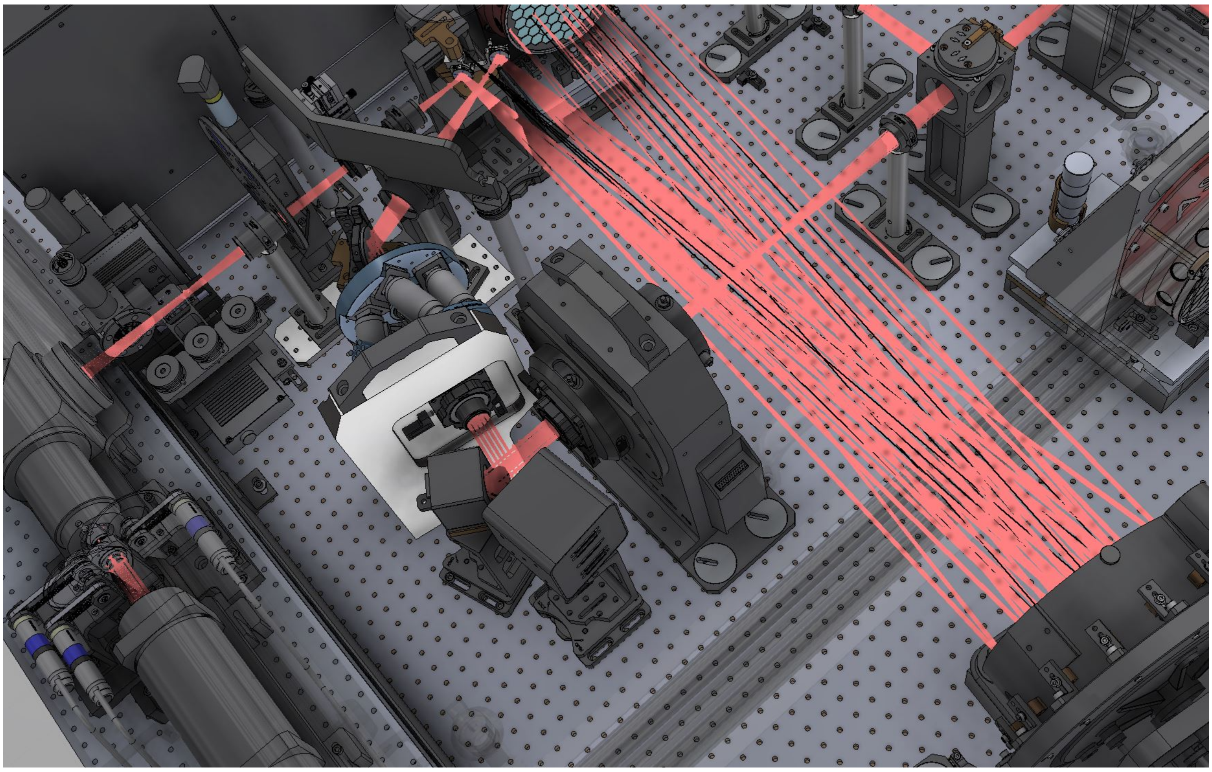

Figure 8: MELT optomechanical design close-up of the telescope emulator part. the beam enters from the left, passes MLGs 1 and 2 while going through the optional spider mask before going through a focal plane and diverge onto the off-axis parabola, which is passed a second time (double pass) after having been collimated onto the ASM with its 61 segments on a 15cm diameter pupil. The converging beam goes after hitting a smal folding mirror another inacccessible focal plane, and MLG3 is used to condition the beam for the M2 assembly (after passing at high incidence off a fold mirror). MLG5 after the hexapod, M4, M5 and the reotator unit with MLG6/1 at the entrance are the next stations for the beam. It then exits the figure on the upper right side.

4. STANDALONE CONTROL STRATEGY

Our control strategy is that we will interface most motors and other devices through a Beckhoff PLC and a rough device level control software possibility in local mode will be provided. Especially during the alignment process, this will be very helpful, but also during the MELT runs for maintenance purposes. The CCS network is interfaced with this PLC and it will be decided on a device by device bases, whether the transformation from MELT interface to ELT-like interface is carried out on the PLC side or the CCS side with a pre-processing SW module.

The MELT electronics are mostly restricted to moving motors of translation stages or filter wheels. Calibration sources need to be turned on/off, and detectors must be interfaced. The control of the ASM stays as it was for APE in a VME crate and with VLT software, which is then interfaced to the ELT CCS such that it shows for it as if the ELT M1 mirror is controlled. The rotator will be controlled maybe with an ELMO controller or Beckhoff solutions, which then will interface to the PLC and controllable of it. The Hexapod is delivered with its own controller, and an API interface to the PLC is possible so that with a transformation box, the CCS controls the MELT hexapod as if it was controlling the M2 hexapod. The 2 tip/tilt mirrors, M5 and pupil stabilization, are controlled with its own Newport controller, which accepts +/-10V analog inputs.

These MELT local control units will be in the former APE electronics cabinet that used to host the WFS LCUs. Because not all are in usage anymore, space is freed, which will be used for the new MELT electronics.

The general CCS part is in the computer room, and the only connection to the local control and hardware is done via fiber, like in the ELT.

5. OUTLOOK AND AY TOWARDS THE PDS

The current schedule aims to have the optics, for which the procurement process with a request for information and a subsequent request for quote was carried out, delivered in October 2018. The final design adaptation with the supplier of the optics is are currently under way, and we are in the process of finalizing the list of all new translation stages and other optomechancis. We are aiming to reuse as much as possible optomechanics, already on the bench from APE. The general newly needed electronics are in the process of currently being ordered. The development of the local control software on the PLC will directly start after the hardware is in house and in fall, when the optics arrive, integration on the bench can start with all optomechanics and local control electronics in place. We expect the rotator prism to arrive in December. By the end of 2018, MELT is planned to be ready optomechanically and controllable via local control SW. The PDS technical specifications need to be written by August 2019. This does not leave lots of time with MELT to identify relevant input and already decide on all critical technical specifications. However, as the PDS is planned with a 1-year PDR, 1-year FDR, and 2-year MAIT phase, not much room is left to postpone the deadline for its specifications further. The PDS will naturally have to be designed in a flexible way as this verification tool will also be used to detect and sense the unforeseeable problems. However, as this document has shown, there are many areas, where detailed information is available and some modules of the PDS are soon to be well defined.

6. CONCLUSION

We have presented the systems engineering and detailed design approach, used for the MELT project within the ELT program. Close proximity (thematically) to the phasing and diagnostic station has been shown and discussed. MELT has already been used to develop the design strategy for the PDS and will in the future help to derive its technical specifications. With its capability to adapt to new or other wavefront control strategies, which can be developed, tested and quantitatively analysed, MELT enables us to find the best starting strategy, when this task is to be used at the ELT. In addition, the central control system of the ELT can already now interface with real hardware and validate software work on the bench that is outsourced. Over the following years, the presented design will most certainly not stay static, but exhibits changes to the needs that result from the usage of MELT. We hope that this learning experience will help us prepare for the ELT commissioning, as discussed at the beginning.

ACKOWLEDGEMENT

The authors would like to thank the entire APE team for their work, which provides the grounds used to extend on with the present project.

REFERENCES

[1] Lewis, S.A.E., Brunetto, E., Förster, A., Frank, C., Guidolin, I., Guisard, S., Hammersley, P., Holzlöhner, R., Jolley, P., Kosmalski, J., Lampater, U., Marchetti, E., La Penna, P., Pfrommer, T., “Extremely Large Telescope Prefocal Station A System Concept”, Proc. SPIE, 10700-43, (2018).

[2] Bonnet, H., Vernet, E., Biancat-Marchet, F., Madec, P.-Y., Esselborn, M., Marchetti, E., Paufique, J., Le Louarn, M., Oberti, S., Stroebele, S., " Adaptive Optics at ESO’s ELT", Proc SPIE, 10703-37, (2018).

[3] Holzlöhner, R., Kellerer, A., "Sensitizer software", ESO 6 June 2018, https://www.eso.org/sci/facilities/develop/software.html (6 June 2018).

[4] Gonté, F., Araujo, C., Bourtembourg, R., Brast, R., Derie, F., Duhoux, P., Dupuy, C., Frank, C., Karban, R., Mazzoleni, R., Noethe, L., Surdej, I., Yaitskova, N., Wilhelm, R., Luoung, B., Pinna, E., Chueca, S., Vigan, A., "Active Phasing Experiment: preliminary results and prospects", Proc. SPIE 7012, (2008).