4MOST Fiber Feed Concept Design

Dionne M. Haynes*[a], Roland Winkler[a] , Allar Saviauk[a], Roger Haynes[a], Samuel C. Barden[a], Olga Bellido-Tirado[a], Svend-Marian Bauer[a], Roelof S. de Jong[a], Eric Depange[c], Frank Dionies[a], Katjana Ehrlich[a], Andreas Kelz[a], Will Saunders[b], Manfred Woche[a],

[a]Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany;
[b]Australian Astronomical Observatory, 105 Delhi Road, North Ryde, NSW 2113, Australia
[c]South African Astronomical Observatory, Observatory road, Observatory, 7925, South Africa

ABSTRACT

4MOST, the 4m Multi-Object Spectroscopic Telescope, features a 2.5 degree diameter field-of-view with ~2400 fibers in the focal plane that are configured by a fiber positioner based on the tilting spine principle (Echidna/FMOS) arranged in a hexagonal pattern. The fibers feed two types of spectrographs; ~1600 fibers go to two spectrographs with resolution R>5000 and ~800 fibers to a spectrograph with R>18,000. Part of the ongoing optimization of the fiber feed subsystem design includes early prototyping and testing of key components such as fiber connectors and fiber cable management. Performance data from this testing will be used in the 4MOST instrument simulator (TOAD) and 4MOST system design optimization. In this paper we give an overview of the current fiber feed subsystem design, simulations and prototyping plans.

Keywords: Multi-object spectroscopy, Astronomical instrumentation, Optical fibers, Fiber mapping, Multi-fiber connector, Fiber feed, FRD, Instrument simulator.

1. INTRODUCTION

4MOST is a wide-field, high-multiplex spectroscopic survey facility[1,2,3] under development for the VISTA telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology[4,5]. 4MOST will in particular provide the spectroscopic complements to the large area surveys coming from space missions like Gaia, eROSITA and Euclid, and from ground-based facilities like VISTA, VST, DES, LSST and SKA. 4MOST features a 2.5 degree diameter field-of-view with ~2400 fibers in the focal plane that are configured by a fiber positioner based on the tilting spine principle (as in Echidna/FMOS)[9]. The fibers feed two types of spectrographs; ~1600 fibers go to two spectrographs with resolution R>5000 and ~800 fibers to a spectrograph with R>18,000. Both types of spectrographs are fixed-configuration, three-channel spectrographs. 4MOST will have an unique operations concept in which 5 year public surveys from both the consortium and the ESO community will be combined and observed in parallel during each exposure, resulting in more than 25 million spectra of targets spread over a large fraction of the southern sky.

The 4MOST fiber feed sub-system optically connects the fiber positioner to the spectrographs and may be regarded as two distinct sections: The first section is called the Short Fibers (SF) and runs from the fiber positioner spine tips to the fiber connector unit. This section includes the fibers mounted in silica or ceramic ferrules at the spine tips, one side of the fiber connectors and the first level of positioner to spectrograph fiber mapping. The second section is called the Fiber Cable (FC) and runs from the fiber connector unit to the spectrograph slit unit. This second section includes the other side of the connector unit, second level of fiber mapping, fiber strain relief, the main telescope cable run, the fiber de-rotator unit, the fiber cable altitude wrap, and the spectrograph slit units. The fiber mapping scheme is complex and has been driven by the desire to have fibers for each spectrograph evenly distributed across the entire telescope field of view, as this mapping negates the risk of field loss if a spectrograph is offline for technical reasons. The positioner spine to spectrograph mapping has a significant impact on the fiber feed and dictates much of the fiber layout, modularity and routing and it is for this reason that multi-way fiber connectors are proposed in order to facilitate 4MOST assembly,

*dhaynes@aip.de; phone +49 331-7499-674; fax +49 331-7499-436

integration, maintenance and VISTA routine maintenance e.g. M1 removal.

Part of the ongoing optimization of the fiber feed subsystem design includes early prototyping and testing of key components such as fiber connectors and fiber cable management. Performance data from this testing will be used in the 4MOST instrument simulator, “Top of Atmosphere to Detector” (TOAD)[14] and 4MOST system design[3] optimization. In this paper we give an overview of the current fiber feed subsystem design, simulations and prototyping plans.

2. FIBER FEED DESIGN

2.1 Optical fiber and throughput

Based on maximizing signal to noise for science targets and spectrograph resolution requirements[4], the optimum fiber is a step-index, multimode silica fiber with a core diameter of 85 um, cladding diameter of ~107 um, and numerical aperture (NA) of > 0.167. Fiber throughput is important to the instrument performance, impacting exposure times and therefore survey efficiency. Fiber throughput is affected by bulk attenuation, focal ratio degradation (if light is coupled to radiation modes), connector losses and Fresnel losses. Instrument performance is also significantly impacted by fiber focal ratio degradation (FRD), which causes a loss at the spectrograph collimator[6]. Therefore the optical fiber material selection is driven by; low attenuation and low intrinsic susceptibility to focal ratio degradation. Broadband optical fiber from Polymicro (FBP) is proposed because it has low attenuation characteristics over the 4MOST wavelength range (390 – 910 nm) and intrinsically low focal ratio degradation[7].

There are three main phenomena that can contribute to FRD within the fiber: scattering, diffraction and modal diffusion[8] (FRD due to fiber/spine tilt is not addressed in this paper). These effects are influenced by various factors, including material irregularities (impurities and variations in the density of the glass), fiber geometry irregularities (changes in concentricity, variations in circularity and diameter of the fiber) which are intrinsic to the fiber and are under the control of the fiber manufacturer; and macro-bending, micro-bending, end-face surface roughness, sub-surface damage caused by the lapping/polishing process and fiber geometry are factors induced by the way the fibers are prepared, handled and deployed. Some of the contributions to FRD can be very sensitive to the external environment making it difficult to accurately quantify in a laboratory environment. Preliminary FRD tests indicate an approximate loss of 10%, for an input beam of f/3.32 coupled with a spectrograph collimator beam speed of f/3.0 (f/3.32 and f/3 corresponding to the current baseline design). The 10% also includes an estimate of additional FRD that can be expected from the fiber connector, the estimate was based on previous connector testing[11] using a different fiber type. A more accurate and detailed loss estimate will be calculated from the fiber cable prototype testing that will take place before the end of 2014 (see section 3).

Broadband anti-reflective coatings at the spine tip end can reduce the Fresnel losses at fiber input and similarly at the slit end by immersing the fiber ends against an AR coated lens. However, producing high quality AR coatings on fiber tips is currently somewhat risky and therefore we accounted for the loss from Fresnel reflection to be ~4%. Fiber AR coating technologies will be monitored and reviewed during 4MOST preliminary design (PD) phase.

The current fiber routing design concept has ~15-meter fibers from the focal surface to the LR (low resolution) spectrographs and ~20 meters to the HR (high resolution) spectrograph. Using fiber attenuation data provided by the manufacturer, an estimation of the throughput for 15 and 20 meter fiber lengths is shown in Figure 1. It is clear from the plot that fiber length has a significant impact on blue throughput, therefore minimizing the optical fiber length is essential for the instrument performance. The fiber feed system loss is estimated to be approximately 16%. The breakdown is as follows; ~4% Fresnel loss at fiber input, ~1% loss in throughput at the connector, ~1% Fresnel loss at fiber slit and ~10% FRD loss at the collimator.

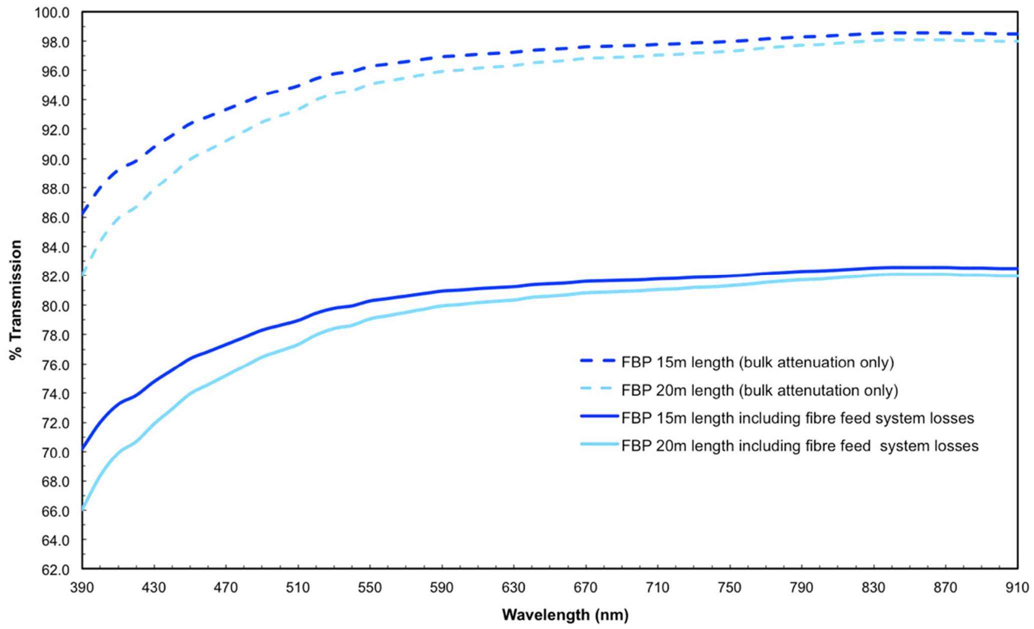


Figure 1. FBP Broadband fiber transmission plots for fiber lengths of 15 and 20 meters.

2.2 Fiber Feed Route

The Fiber Feed consists of two major cables, the Short Fiber cable (SFC) with the individual ferrules on one end and the connector on the other end; and the Fiber Cable (FC) with the connector on one end and the spectrograph slit blocks on the other end. The SFC is routed from the individual fiber spines through a mapping layer to the fiber connectors. The FC is routed from the connectors through another layer of mapping and cable management, the fiber cable de-rotator unit, the fiber cable Altitude wrap, and fiber cable strain relief box to the spectrographs. The fiber cable de-rotation unit facilitates field rotation during observation, the fiber cable Altitude wrap allows telescope altitude motion, and the fiber strain relief box assists assembly and ensures free movement of the fibers for the 4MOST lifetime. The fiber connector assembly provides a connection/dis-connection point directly behind the fiber positioner to facilitate installation and removal, modular assembly and mapping, maintenance/repair and independent verification testing of the fiber positioner.

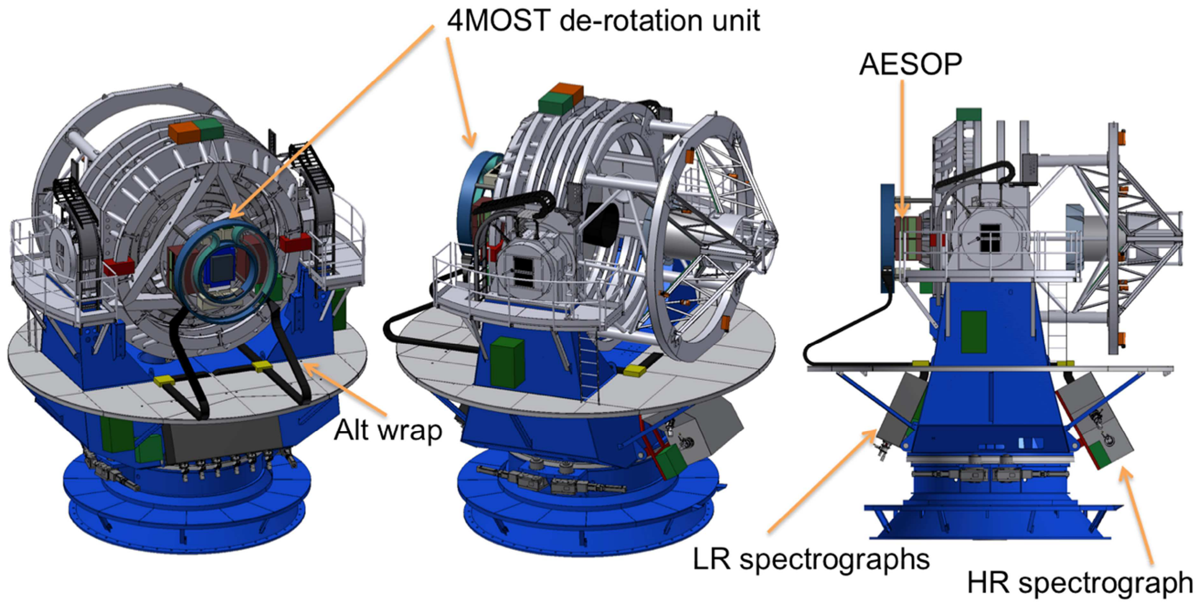


Figure 2. VISTA 3D CAD model with 4MOST instrument.

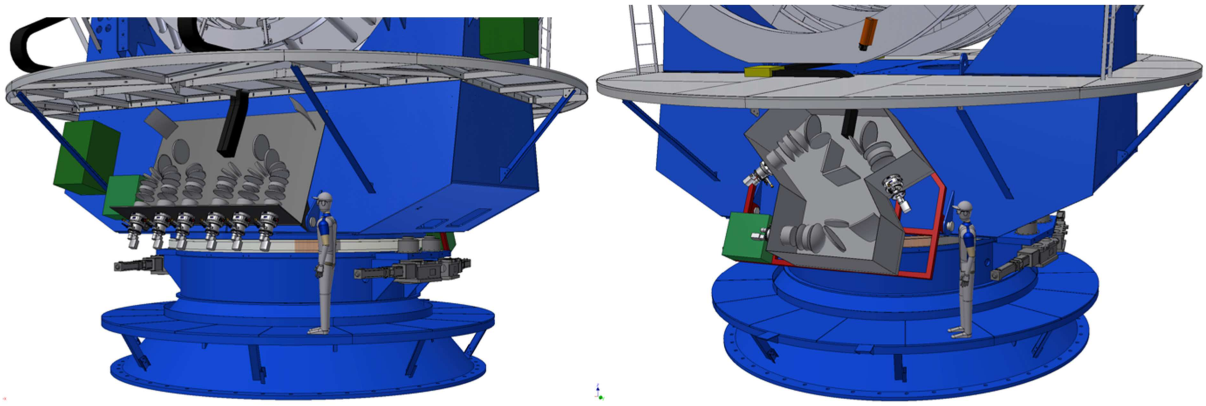


Figure 3. VISTA 3D CAD model. Left: location of LR spectrographs, showing the proposed routing of the fiber cables (black cable tray) to the spectrographs, Right: location of HR spectrograph showing the proposed fiber cable routing (black cable tray) to the spectrograph.

The fiber cables exit from the back of AESOP[10] (Australian ESO Positioner) through a fiber connector and the cables are then grouped for entry into the de-rotation unit (represented as the blue ring structure Figure 2). LR-A cables and HR cables are fed to the right energy chain in the de-rotator and LR-B cables are fed to the left energy chain of the de-rotator (represented by the olive ribbons). The fiber cables exit from the de-rotator to the left and to the right and immediately enter the Altitude cable wraps (represented as the black chain). The fiber cables are then routed through the fiber strain relief unit (represented as the yellow boxes) to the spectrographs. The LR spectrographs are attached to the telescope fork under the azimuth rotating floor at the back of the telescope and the HR spectrograph is attached to the telescope fork under the azimuth rotating floor at the front of the telescope. The VISTA service de-rotator has been removed to allow shorter fiber lengths and the necessary space for AESOP. 4MOST has its own cable de-rotation unit, which carries the fiber cables and the necessary instrument services.

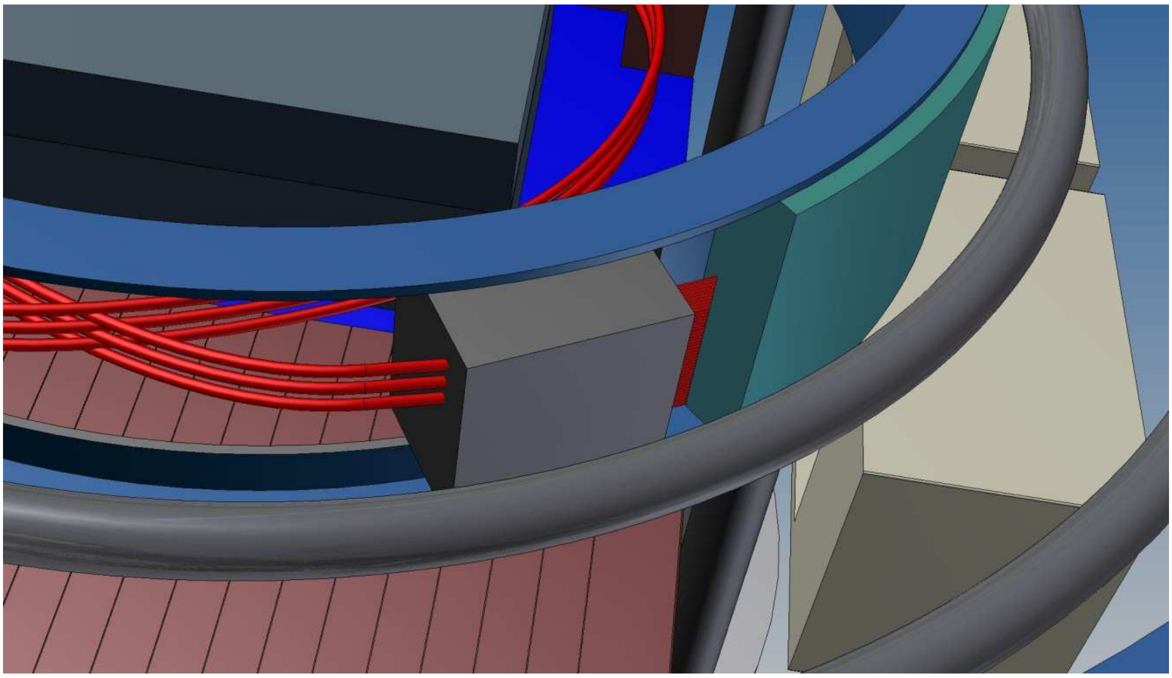


Figure 4. Fiber conduit entering the second layer mapping box and exiting as a ribbon of 28 fiber conduits that go thorough the de-rotation unit.

Figure 4 shows the fiber conduit coming from the positioner to the second layer mapping box where the fibers are gathered into groups of 29 and re-cabled to form a ribbons consisting of 28 fiber conduits to enter the fiber de-rotation unit. The second layer mapping box contains the Miniflex m2fx Duplexers that are proposed in section 2.5 as part of the cable management.

2.3 Fiber Connector

To facilitate 4MOST assembly, integration, and maintenance (i.e. VISTA M1 removal) we propose using multi-fiber connectors. Based on prototype tests carried out in 2009/2010 MTP USConec connectors are proposed for 4MOST. The preliminary results[11] showed that when care is taken to assemble and polish these connectors carefully, the throughput can be 98% or better, and FRD is minimal (i.e. Encircled energy reduction of 4 - 5 % for an input beam of f/4). It was also demonstrated that wavelength fringing caused by an air gap in the connector can be successfully negated by the use of index matching gel[11]. We are confident that the FRD can be reduced further with the use of a low shrinkage epoxy like Epotek 301-2 epoxy and operating at faster beam i.e. 4MOST input beam speed f/3.32.

USConec MTP MM Elite® multimode MT ferrules are proposed as they have the strictest alignment tolerances and hence the lowest insertion losses. The MTP MM Elite® is currently available in 12, 16, and 24 fiber densities for standard telecommunications multi-mode fiber which has an outer diameter of 125um. Custom connectors for different fiber counts and fiber outer diameters are possible, however this is not necessary for 4MOST as the fiber outer diameter including buffer is 123µm and will fit into the commercial off-the-shelf (COTS) connector ferrules.

The spectrograph fiber mapping and current AESOP module modularity determines the number of connectors per module and connector ferrule fiber densities, i.e. 6 connectors per module containing between 10 to 19 fibers each depending on the spine population of the module.

The fiber connector assemblies will likely be mounted on the fiber support frames of AESOP. This aids assembly and maintenance as each spine module can be independently removed from the positioner assembly. In order to facilitate the fiber mapping the connectors are further grouped into LR-A fiber connectors (56 units), LR-B fiber connectors (56 units), HR fiber connectors (56 units), see Figure 7. The connector housing may also be color-coded and keyed by spectrograph group with the use of USCONEC MTP Secure™ connectors.

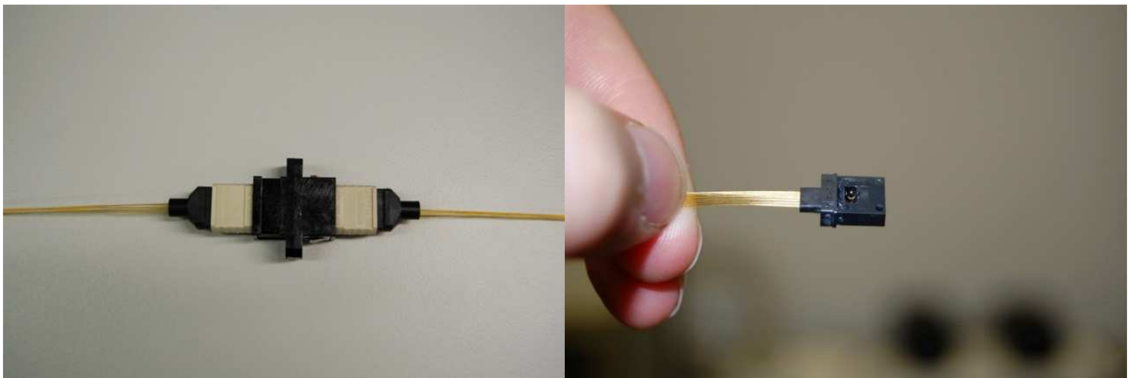


Figure 5. USConnec MTP connectors prototyped at AAO/AIP in 2009/2010[10]. Left – 12 fiber MTP test connector unit and adapter fully assembled with astronomy grade fiber, Right – 12 fiber MT test ferrule assembled with astronomy grade fiber.

2.4 Fiber Mapping

The positioner spine to spectrograph mapping has a significant impact on the fiber feed and dictates much of the fiber layout, modularity and routing. The 4MOST spectrograph groups are defined as LR-A, LR-B and HR, i.e. two low-resolution spectrographs and one high-resolution spectrograph. Figure 6 shows the proposed fiber layout at the positioner. Module identification numbers are at the top of the image, and spine counts per row are indicated at the bottom of the image. The positioner spines are arranged such that each row of spines has alternating LR-A, LR-B and HR fibers.

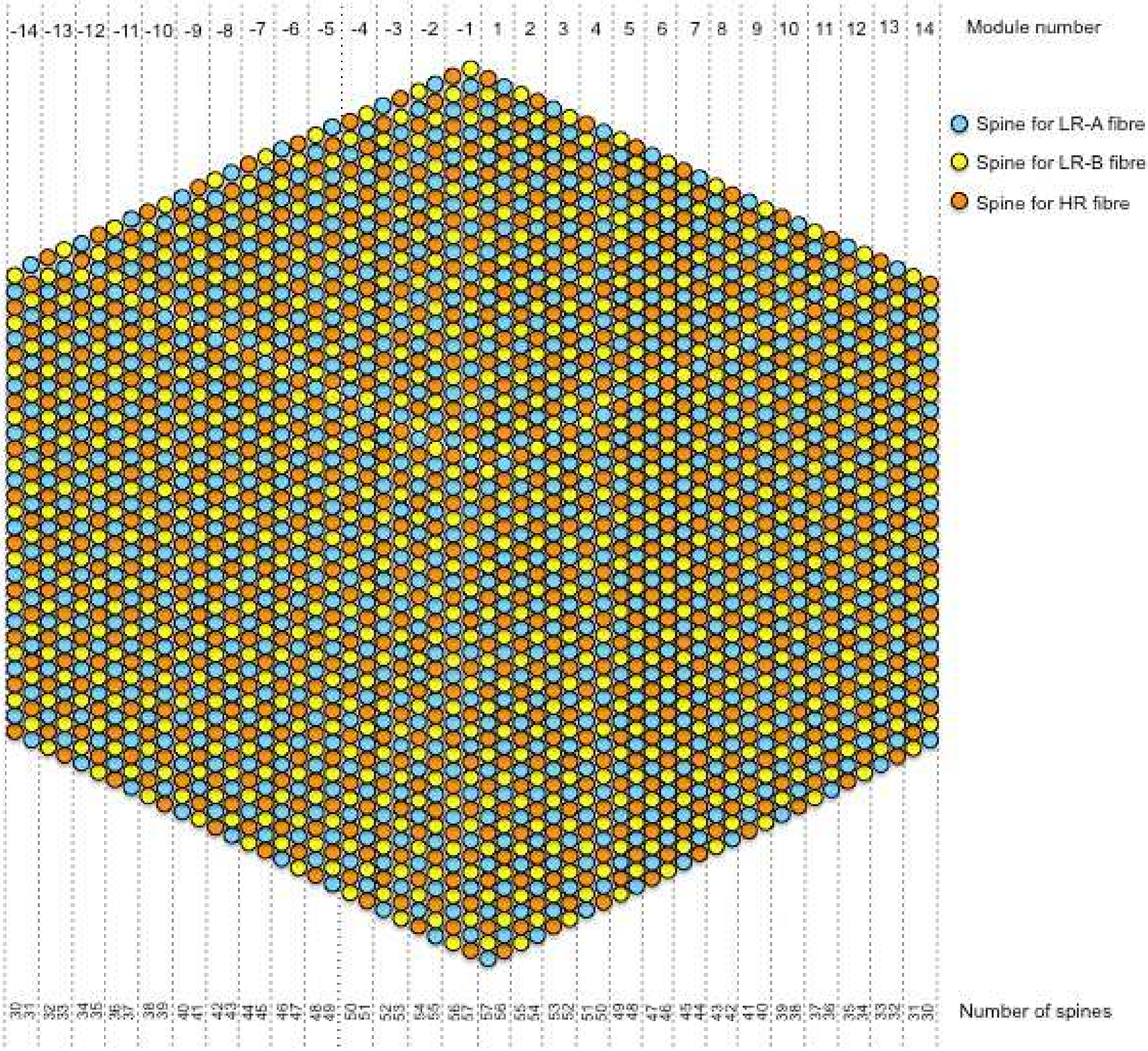
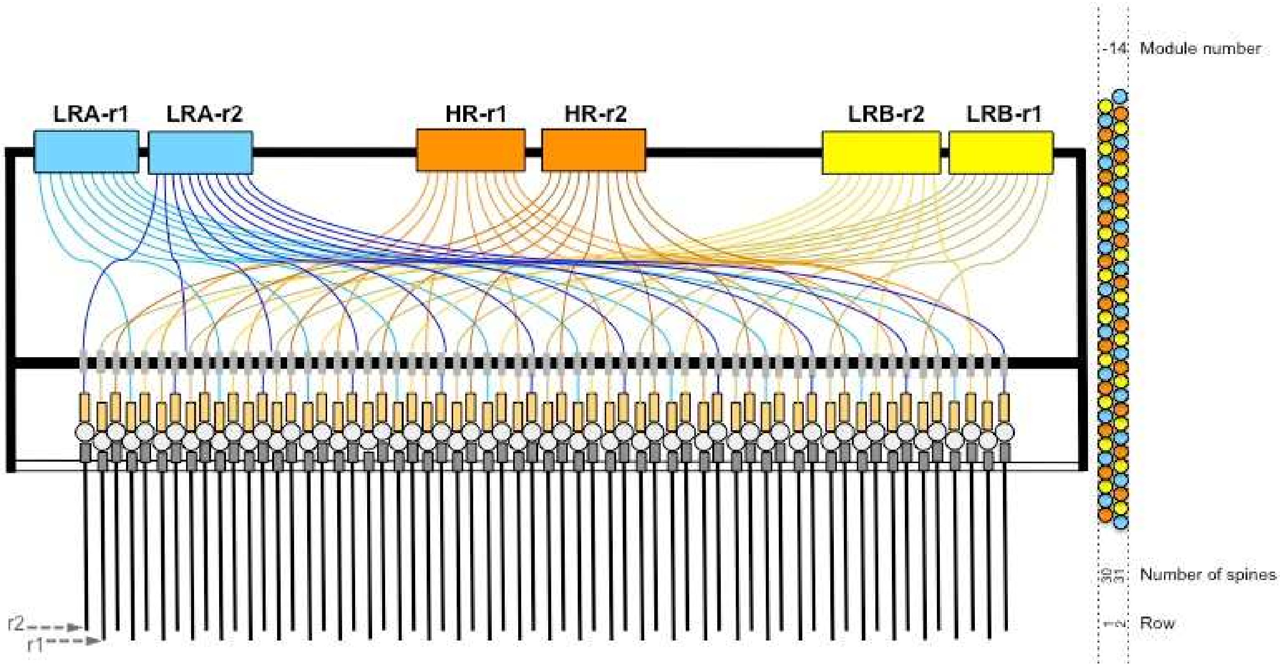


Figure 6. Proposed 4MOST fiber positioner (AESOP) spectrograph mapping layout.

The complex mapping shown in Figure 6 has been driven by the desire to have fibers for each spectrograph evenly distributed across the entire field. This mapping negates the risk of field loss if a spectrograph is offline for technical reasons. The fiber positioner to spectrograph mapping consists of two layers. The first layer mapping is the positioner module to spectrograph group shown in Figure 6 & 7, and the second layer mapping consists of grouping the spectrograph groups from different positioner modules to facilitate modularity for the spectrograph slitlets. This is done over the two halves of the positioner by pairing the spectrograph groups from module 1 and module 14, module 2 with module 13, module 3 with module 12, module 4 with module 11, module 5 with module 10, module 6 with module 9, and module 7 with module 8. If one pairs the longest row of one module with the shorter row of the other module it results in the same number of fibers for each spectrograph group. The magic number for the fiber positioner spectrograph group to spectrograph group slitlet modularity is 29.



7. Diagram representing module -14, showing the first layer of mapping for the positioner to spectrograph group. Each module has 6 connectors mounted on the top of the fiber support bridge, two LR-A, two LR-B and two HR. The connectors are further grouped into r1 and r2, representing the two rows of fibers in the module, it is necessary to have this extra grouping to facilitate the second layer mapping (spectrograph slitlet modularity).

2.5 Fiber Conduit and cable management

Miniflex™ Protection Tube (as used in FMOS[12]) is proposed as the fiber conduit material for 4MOST. It is flexible tube made from tough polymers to protect optical fibers. It is lightweight, compact, flexible, has anti-kink property, very high crush resistance, and compatible with MTP fiber connection termination methods. Miniflex™ Protection Tube is available in 7 different material types, however PBT material has the highest crush and tension resistance (see Table 1) for the small diameter tubes and is therefore the material we have selected. The SFC section we propose to use the tube size, which has an inner diameter (ID) of 1.4 mm and outer diameter (OD) of 3.0 mm, which will carry between 10 and 19 fibers from the connectors. The FC section will use a slightly larger tube of ID 3.1 mm and OD of 5.0 mm and will carry 29 fibers per length. Miniflex m2fx Duplexers are proposed for the cable management in the second layer mapping box. The Duplexer is a bifurcation manifold that enables multi-fiber cables to be divided or combined.

Table 1. Miniflex fiber protection tube specification for SFC and FC sections.

Miniflex Protection Tube	SFC conduit	FC conduit
Material	PBT	PBT
OD - outer diameter (mm)	3.0	5.0
ID – inner diameter (mm)	1.4	3.1
Crush (N)	950	1400
Tension (N)	140	280
Nominal weight (kg/km)	8.1	13.6
Bend radius (passive)	10 x OD	10 x OD
Bend radius (active)	5 x OD	5 x OD
Install Temp (Celsius)	-10 to +60	-10 to +60

2.6 Fiber De-rotator

The fiber de-rotation unit shown in Figure 8 protects and guides the fibers during instrument rotation. It has been designed to accommodate 360 degrees of instrument and telescope rotation and has two identical energy chains, one feeding to the left for LR-A spectrograph and one feeding to the right for LR-B and HR spectrographs. The de-rotator structure consists of an inner and outer ring that guides the energy chain in an axial position. The inner ring rotates with respect to the outer ring. The inner ring has an inner diameter of 1400 mm and is connected to the instrument rotator and the outer ring has an outer diameter of 2600 mm and is connected to the telescope structure. One end of each energy chain is connected to the inner ring and the other end to the outer ring. The horseshoe shaped rail guides and supports the energy chain and prevents it from collapsing. Small rollers are connected to the inner side of the energy chain and roll on the horseshoe part, which acts as a guide rail. The depth of the de-rotator is ~300mm and the bend radius of the fiber cable ribbon at the neutral face is 250mm, this is well in excess of the 100 mm minimum bend radius required to prevent degradation of fiber performance. The fiber cable ribbon on the left side of the de-rotator is composed of 28 x 5 mm OD Miniflex protection tubes (all LR-A fibers), resulting in a ribbon that is ~5 mm thick and ~140 mm deep. The fiber cable ribbon on the right side of the de-rotator is composed of 56 x 5 mm OD protection tubes in total comprised of two 28 x 5 mm OD fiber cable ribbons ~5 mm thick and 140mm deep. One ribbon contains all of the LR-B fibers and the other ribbon contains the HR fibers. To balance the weight distribution in the left and right chains of the de-rotator, it is envisaged that most of the other telescope services will run through the left chain. The size of the de-rotator inner ring diameter is driven by the need to for clear access to the AESOP positioner modules such that individual modules can be removed for maintenance and repair. For instrument removal the entire de-rotator has to be un-bolted and moved as an entire assembly including the altitude wrap energy chains.

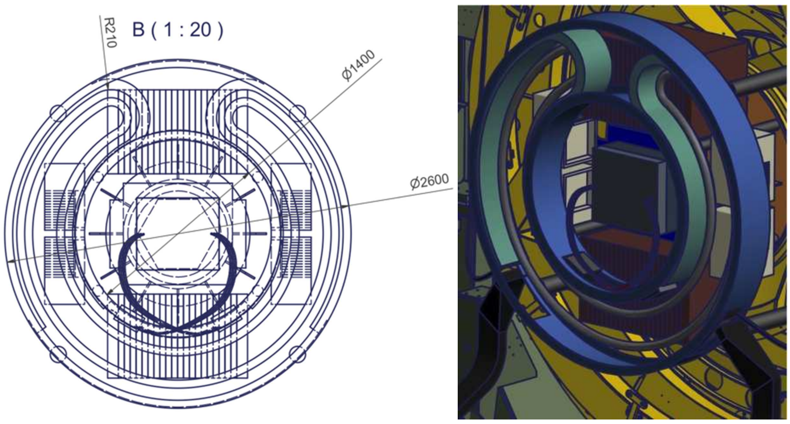


Figure 8. 4MOST fiber cable de-rotator

2.7 Fiber Altitude wrap

The main function of the altitude fiber wrap is to protect the fibers during telescope altitude motion. There are two fiber cable altitude wraps in the 4MOST instrument concept, one coming from the left cable exit of the de-rotator and one coming from the right cable exit of the de-rotator feeding the fibers to the LR-A and LR-B & HR spectrographs respectively. We propose to use igus® system E6 energy chain as it has been specifically developed by industry to guide and protect moving cables and hoses extremely quietly with minimal vibration.

2.8 Fiber strain relief

Fiber strain relief units, to mitigate build up of tension/compression in the fibers, are included in the fiber run between the altitude wrap and the spectrograph slit units. In addition the strain relief units help facilitate the maintenance, assembly and integration (MAI) of the fiber bundle, providing a mechanism to compensate for small variations in fiber length and routing. Currently the concept has not been greatly advanced and that presented by Murray, et al[12] for FMOS is the baseline concept. However, detailed development is anticipated during the PD phase.

2.9 Spectrograph slit units

Spectrograph slit units are typically composed of a series of slitlets containing a small fraction of the total number of fibers in the full spectrograph slit. The 4MOST slitlet approach simplifies modularity, manufacture and assembly of the fiber slit. The main design consideration for the slitlet modules is the precision alignment (x, y, z, θx, θy) of the fibers. There are various ways to achieve accurate alignment, however, silicon v-groove chip technology is the concept proposed for 4MOST. These v-groove assemblies are available with custom spacing and numbers of v-grooves with a pitch accuracy of ±0.5μm.

Fiber slitlets for Low-resolution spectrograph

The Low Resolution Spectrograph slit units consist of 28 slitlet modules, each module containing 29 fibers. The proposal is to use silicon v-groove technology for the fiber slitlet modules, shown in Figures 9. The slitlets will be arranged into two separate slit units, one composed of the LR-A fibers and the other composed of the LR-B fibers. Each of the slit units contains 812 science fibers. We propose to immerse the slitlet fibers against a lens that has numerous benefits i.e. accurate positioning of slitlets by an optical surface, reduced scattered light from fiber end-face surface roughness using index matching gel, an anti-reflection coating can readily be applied to the outside optical surface of the lens[13].

A 3D CAD model of the Low Resolution spectrograph slit concept is shown in Figure 10. A total of 28 slitlet modules are accurately positioned and immersed against a lens. The slit units shown still has a gap of ~17 mm, in the middle of the slit, which corresponds to a gap between the two detector (in each camera envisaged at CDR). The latest LRS design developed during the optimization phase has a single 6Kx6K detector per camera, so the gap would no longer be necessary. The slitlets are grouped in two sections: 14 slitlets above the gap and 14 slitlets below the gap. Up to 6 calibration fibers could be incorporated if necessary with 6 of the slitlet modules manufactured to contain 30 fibers (29x science + 1x calibration) to accommodate the calibration fibers.

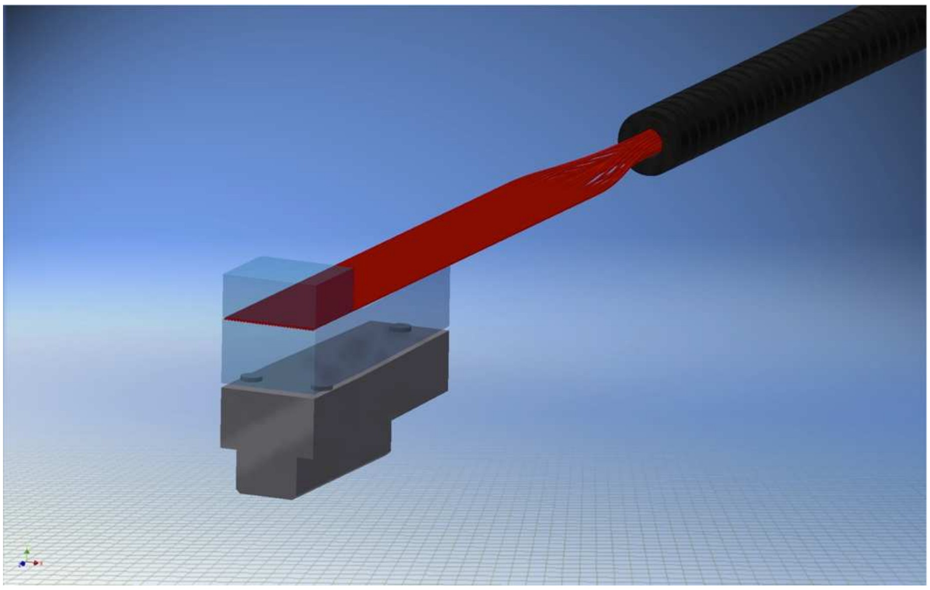


Figure 9. 3D CAD model of concept slitlet module containing 29 fibers, mounted on stainless steel positioning block. Using silicon or glass v-groove technology the fibers are located in the precision v-grooves with a Pyrex lid held in place by EPOTEK 301-2 epoxy. The v-groove blocks have a 3-point contact base and are accurately fixed to the stainless steel blocks using epoxy.

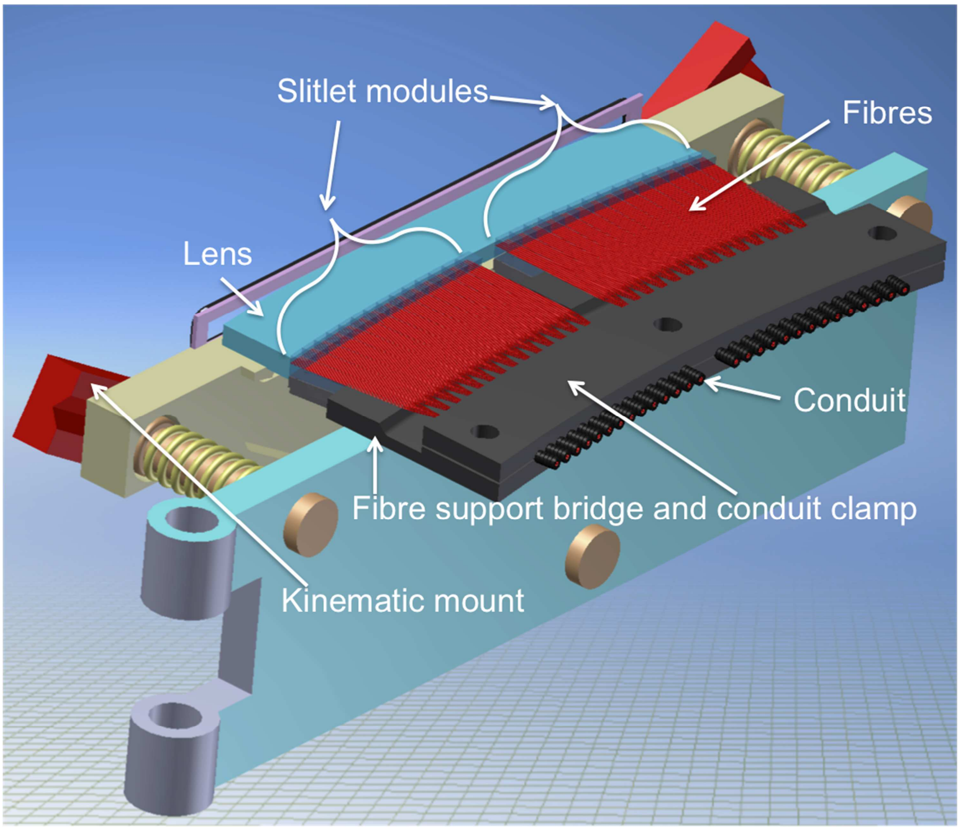


Figure 10. 3D CAD model of Low Resolution Spectrograph slit design showing the slitlet modules positioned and immersed against a cylindrical lens.

Fiber slitlets for High-resolution spectrograph

The High Resolution Slit concept is similar to the Low Resolution concept, with each module containing 29 science fibers. To allow for up to 10 calibration fibers 10 modules could contain 30 fibers. The slit shape is also curved and a lens of the correct curvature is also used for aligning and positioning the slitlet modules.

2.10Fiber Health monitor

The fiber cable health will be monitored using the fiber flat field data. The performance of each fiber will be regularly logged and significant changes in performance will be flagged. We also propose a more advanced health monitoring system in which Fiber Bragg gratings are used as strain and bend sensors within the length of the fiber cable. It is possible to have a number of FBGs along the length of the sensing fibers such that strain and bend can be measured independently at a number of locations within the fiber cable. We propose to measure the strain at 4 locations; the fiber length that runs from the connector to the de-rotator entry, the fiber length that runs through the de-rotator, the fiber length that runs through the altitude wrap and the fiber length between the alt wrap and the strain relief box. The strain/bend can be monitored at all four locations within the fiber cable in real time and can therefore be connected to safety switches that halt the movement of the instrument and telescope if the strain or bend exceeds at certain threshold to prevent fiber and instrument damage.

3. FIBER FEED PROTOTYPING

The Fiber Feed prototype has three major objectives:

- Prototyping of critical components that impact the overall design choices
- Enable effective system design to maximize the amount of light transferred from the fiber positioner to the spectrograph slits
- Develop subsystem performance model for TOAD

The aim is to clarify the specifications of the various components that make up the baseline fiber feed design from the positioner spine tips through to the envisioned spectrograph slitlets. We have procured a set of these components for the fabrication and evaluation of a set of prototype fiber cables. Test equipment necessary to perform FRD, spectral throughput, wavelength fringing, modal scrambling and modal noise testing of the fiber cables with a pupil illumination representative of the VISTA pupil with tilt adjustment representative of spine tilt has been designed and built.

A full trade-off study between fiber connectors and fiber splicing will be undertaken; this includes optical performance, manufacturability, quality control, integration and MAIV.

All fiber feed performance test results will be documented and provided in a format compatible with the 4MOST instrument simulator TOAD.

4. 4MOST INSTRUMENT SIMULATOR (TOAD)

During the development of the 4MOST instrument, a tool for systems engineering[15] is required, that can simulate the impact of design decisions on the performance of the instrument. To achieve this, requires the accurate simulation of all optical effects. TOAD is organized into software modules (discussed in these proceedings) [14] such that a light plane is passed through the modules and is altered by each module according to their optical effects. This design is very flexible, any module is easily exchangeable and it is easy to insert a light plane at any point in the light path. One of these modules, the fiber module, has a significant impact on the performance of the instrument and should therefore be as accurate as possible.

The TOAD fiber module models numerous effects, including

- Input and output losses due to Fresnel reflection at the face of the optical fiber
- Focal ratio degradation (FRD)
- Throughput as a function of fiber length (intrinsic to fiber type i.e. material)
- Throughput losses due to fiber connector and or fiber splice
- Effects of incomplete fiber mode scrambling

Currently TOAD uses estimated FRD losses extrapolated from VIRUS fiber testing. An improved FRD model for the fiber feed will be implemented as soon as the characterization of the prototype fiber cables is performed including the impact of fiber bending through the two cable wraps. It is planned that all the characterization results from the fiber feed prototyping will feed directly into TOAD such that we have an accurate performance model for all of the effects listed above.

AKNOWLEDGEMENTS

We gratefully acknowledge the financial support of the German Federal Ministry of Education and Research (BMBF) through the Verbundforschung (grant no. 05A11BA3) and the Program Unternehmen Region (grant no. 03Z2AN11).

REFERENCES

[1] De Jong, R. S., Barden, S. C., Bellido-Tirado, O., Chiappini, C., Depagne, E., Haynes, R., et al. "4MOST: 4-metre multi-object spectroscopic telescope ", Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 9147-21 (in these proceedings)

[2] de Jong, R. S., Bellido-Tirado, O., Chiappini, C., Depagne, E., Haynes, R., et al. "4MOST: 4-metre multi-object spectroscopic telescope ", Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84460T (October 5, 2012)

[3] Haynes, R., de Jong, R. S., Barden, S. C., Schnurr, Bellido-Tirado, O., et al. "The 4MOST instrument concept overview", Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 9147-243 (in these proceedings)

[4] Schnurr, O., Walcher, C. J., Chiappini, C., Schwope, A. D., Bellido Tirado, O., "From space to specs: requirements for 4MOST", Proc. SPIE 9150, Modeling, Systems Engineering, and Project Management for Astronomy VI, 9150-46 (in these proceedings)

[5] Caffau, E., Koch, A., Sbordone, L., Sartoretti, P., Hansen, C.J., Royer, F., Leclerc, N., Bonifacio, P., Christlieb, N., Ludwig, H.-G., Grebel, E.K., de Jong, R.S., Chiappini, C., Walcher, J., Mignot, S., Feltzing, S., Cohen, M., Minchev, I., Helmi, A., Piffl, T., Depagne, E. and Schnurr, O. (2013), Velocity and abundance precisions for future high-resolution spectroscopic surveys: A study for 4MOST. Astron. Nachr., 334: 197–216. doi: 10.1002/asna.201211814

[6] Parry, I. R. "Optical fibers for integral field spectroscopy", New Astronomy Reviews, Vol. 50, Issues 4-5, p301-304 (2006)

[7] Crause, L., Bershady, M., and Buckley, D., "Investigation of focal ratio degradation in optical fibers for astronomical instrumentation", Proc. SPIE 7014, Ground-based and Airborne Instrumentation for Astronomy II, 70146C (July 10, 2008)

[8] Haynes, D. M., Withford, M. J., Dawes, J. M., Lawrence, J. S. and Haynes, R., "Relative contributions of scattering, diffraction and modal diffusion to focal ratio degradation in optical fibers", Monthly Notices of the Royal Astronomical Society, 414: 253–263 (2011)

[9] Akiyama, M., Smedley, S., Gillingham, P., Brzeski, J., Farrell, T., et al. "Performance of Echidna fiber positioner for FMOS on Subaru", Proc. SPIE 7018, Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, 70182V (July 14, 2008)

[10] Sheinis, A. I., Gilbert, J., Farrell, T. J., Saunders, Waller, L. G., Brzeski, J., Gillingham, P., Muller, R., Smedley, S., Smith, G., "Advances in the Echidna fiber-positioning technology", Proc. SPIE 9151, Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, Paper 9151-67 (June 2014).

[11] Haynes, D. M., Haynes, R., Rambold, W., Goodwin, M., Penny, E. J., "Multi-way optical fiber connectors for astronomy", Proc. SPIE 7739, Modern Technologies in Space- and Ground-based Telescopes and Instrumentation, 773946 (July 20, 2010)

[12] Graham J. Murray ; George N. Dodsworth ; Robert Content and Naoyuki Tamura "Design and construction of the fiber system for FMOS", Proc. SPIE 7014, Ground-based and Airborne Instrumentation for Astronomy II, 70145L (July 11, 2008)

[13] Kelz, A., Roth, M. M., Becker, T., and Bauer, S., "PMAS fiber module: design, manufacture, and performance optimization", Proc. SPIE 4842, Specialized Optical Developments in Astronomy, 195 (2003)

[14] Winkler, R., Haynes, D. M., Bellido-Tirado, O., Xu, W., Haynes, R., "TOAD: a numerical model for the 4MOST instrument", Proc. SPIE 9150, Modeling, Systems Engineering, and Project Management for Astronomy VI, 9150-28 (in these proceedings)

[15] Bellido-Tirado, O., Haynes, R., de Jong, R. S., Schnurr, O., Walcher, J. C., and Winkler, R., "Systems engineering implementation in the conceptual design phase of the 4MOST", Proc. SPIE 9150, 9150–45 (in these proceedings)