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Current Status of the HETDEX Fiber Optic Support System

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ABSTRACT

The Hobby-Eberly Telescope Dark Energy eXperiment [HETDEX] will employ over 43,000 optical fibers to feed light to 192 Visible Integral-Field Replicable Unit Spectrographs [VIRUS]. Each VIRUS instrument is fed by 224 fibers. To reduce cost, the spectrographs are combined into pairs; thus, two bundles of 224 fibers are combined into a single Integral Field Unit [IFU] of 448 fibers. On the input end the fibers are arranged in a square 'dense-pack' array at the HET focal surface. At the output end the IFU terminates in two separate linear arrays which provide entry slits for each spectrometer unit. The IFU lengths must be kept to an absolute minimum to mitigate losses; however, consideration of overall project cost and duration of the science mission have resulted in the generation of two competing concepts. Multiple axes of motion are imposed on the IFUs as they span the shortest distance from the focal surface to each VIRUS unit. Arranging and supporting 96 IFUs, that have a total mass over 450 kg, in a manner that is compatible with these complex translations, together with the management of accompanying forces on the tracking mechanism of the HET, presents a significant technical challenge, which is further compounded by wind buffeting. The longer IFU concept is favored due to overall project cost, but requires tests to assure that the fibers can withstand forces associated with a height differential of 16.25 meters without FRD losses or breakage.

Keywords: Hobby-Eberly Telescope, HET, HETDEX, VIRUS, fiber optics, integral field unit, IFU, focal ratio degradation, FRD, The University of Texas at Austin, McDonald Observatory, Center for Electromechanics, CEM

1. INTRODUCTION

The HETDEX project is a major upgrade to the HET which will enable a vast spectral survey of LAE objects for the purpose of characterization of Dark Energy, in addition to supporting the original science mission and instrumentation of the telescope. HETDEX entails two major hardware upgrades to the HET: 1) a complete overhaul of the top end of the HET including the wide field corrector, tracker and prime-focus instrument package [PFIP], and 2) the fabrication and installation of 192 spectrometers called VIRUS in proximity to the focal surface produced by the telescope. The spectrometers are fiber fed over a wavelength range of 350 to 680 nm, which necessitates minimizing the fiber lengths as much as possible in order to mitigate transmission losses, especially in the 350 to 370 nm range. In this effort numerous concepts have been explored for placing a large number of spectrometers in as close proximity to the focal surface of the telescope as possible, and these fall into three broad categories: 1) direct mounting on the tracker, requiring 4 meters of fiber, 2) mounting in proximity to the upper-hexagon of the telescope, requiring 15 meters of fiber, and 3) positioning of the VIRUS array at the base of the telescope structure, requiring as much as 26 meters of fiber. Direct mounting to the tracker, while offering the greatest throughput, was rejected early on as too technically risky and costly. Numerous incarnations of concepts utilizing the other two locations have distilled down to the designs which will be referred to as Concepts Two and Three, as illustrated in Figure 1.

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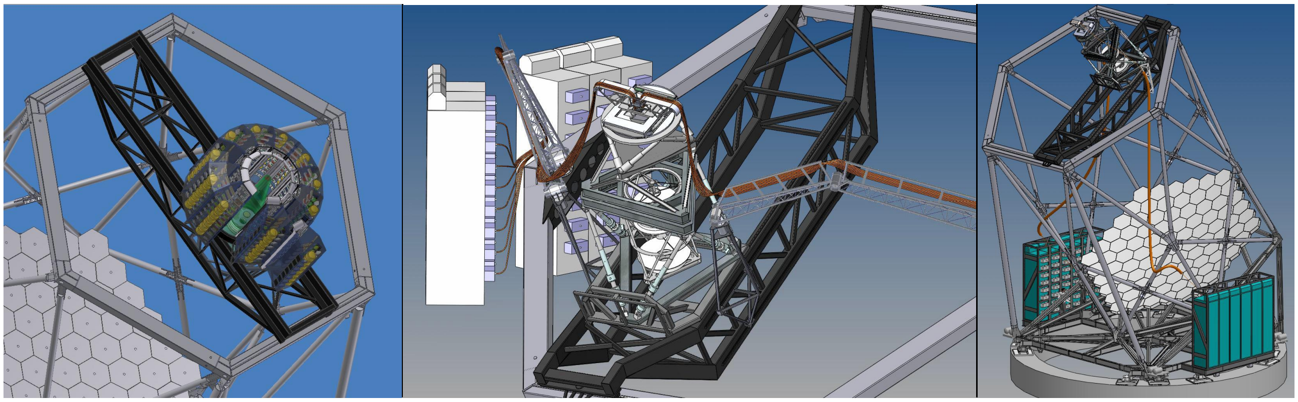


Fig. 1. Three major HETDEX concepts have been developed to explore the trades between fiber length and project complexity and cost. Concept One [left], places VIRUS within the central obscuration of the field of view, but has been ruled out due to technical and cost risk. Concept Two [middle], places VIRUS at the top of the HET, and Concept Three [right], positions VIRUS at the base of the telescope where the fibers are longest but require the least cost to mount and access.

The fibers themselves are contained within an envelope, suitable for protecting and optically coupling as efficiently as possible, called an Integral Field Unit [IFU]. On the input end of the IFU the fibers have a “dense-pack” type design, where 448 fibers are packed as closely together as possible with a fill factor less than unity. The area is filled in during observation by dithering the IFU head on the sky. On the output end of the IFU, the fibers are arranged into two 1 x 224 arrays which serve as the entry slits for a pair of spectrometers. The focal surface of the telescope will be populated by 96 IFUs. Each of the IFUs will feed two VIRUS units, for a total of 192 spectrometers.

2. THE INTEGRAL FIELD UNIT

2.1 IFU General Characteristics

The IFU has been developed and built in partnership with Astrophysikalisches Institut Potsdam (AIP). The optical fibers of each IFU are housed within a flexible, protective conduit. The conduit is a wound corrugated steel design, sealed within a PVC outer jacket. Internally, IFU fibers are surrounded by woven nylon fabric sheathing to reduce friction and prevent abrading with the steel conduit. Each fiber has a core diameter of 265 microns and an area of 1.76 square arcseconds on the sky [1.50 arcsec. diameter] on the upgraded 10 m HET at f/3.65. Conduit fill factor, or the ratio of total fiber cross section area to conduit cross section area, is initially limited at or below one-third. Sufficient unoccupied volume must be allowed within the conduit to accommodate differences in relative length and bend radius between conduit and fiber as each flexes during HET operation. At 30% fill factor, conduit outside diameter is estimated to be 15 mm with a mass per unit length of 235 g/m for each of the 96 IFU and conduit assemblies [total mass = 450 kg].

Several mechanical characteristics influence the design and performance of the IFU conduit assembly. The conduit must have sufficient strength and rigidity to protect each of the 448 fibers housed within from potential mechanical and environmental damage. While the individual fibers will handle a lower bend radius, per specification, a minimum bend radius of 150 mm has been established to assure IFU optical performance, and minimum bend radius of 100 mm has been established to prevent damage to the optical fiber. The conduit shall permit a bend radius of no less than 100 mm during installation and handling, and bend radii less than 150 mm shall be prohibited in operation by either the conduit or fiber optic support system. Additionally, the conduit will have strength and integrity to prohibit tension, compression, and torsion forces in excess of IFU stress and strain survivability limits encountered during normal operation and installation scenarios. Cyclic load limits will be established experimentally in order to extend fiber mechanical life and mitigate focal ratio degradation. Once assembled, the IFU and conduit must be hermetically sealed unit to prevent moisture and particle ingress from reducing fiber life.

Conduit outside diameter, and the resulting conduit profile, contributes to both primary mirror obscuration and the net force the fiber optic support system will experience in heavy wind. Each of these factors may affect HET performance to such a degree that they must be considered among technical design drivers for the HETDEX upgrade. 70% void space is naturally inferred from the 30% conduit fill factor, and by extension the outside diameter has been enlarged accordingly. The squared relationship of internal volume to diameter presents an opportunity to reduce the overall profile of HETDEX's 192 instrument feeds. Packaging 448 fibers per conduit, rather than the 224 of earlier concepts, permits accommodation of the one-third fill factor with reduced mirror obscuration and aerodynamic signature, due to the fact that the number of conduits are reduced by one-half.

2.2 The IFU Head

The VIRUS IFU head serves three functions: 1) hold the individual fibers, 2) provide a means to accurately secure the IFU head to the IFU mount plate, and 3) provide an interface to the conduit protecting the fiber bundles.

The 448 individual VIRUS fibers are held in a hexagonal close pack configuration. The layout of the fibers is illustrated in Figure 2. The arrangement and spacing between fibers were designed to enable full coverage of the sky using three exposures at three dither positions of the input head. Two IFUs have been built for use with the prototype [called VIRUS-P], VP-1 and VP-2. The VP-1 and VP-2 prototype fiber bundles utilize an array of capillary tubes which are first arranged in the desired configuration within the IFU head housing, and then individual fibers are inserted into the capillary tubes.

Each IFU head must be accurately and repeatably secured to the IFU mount plate. The current design, produced by AIP, uses a precision-machined cylindrical plug at the IFU head which is received by a cylindrical receptacle on the IFU mount plate for locating. A pin at one corner of the IFU head is received at the IFU mount plate for keying orientation. Small permanent magnets are used to create axial holding force between the IFU head and mount plate. This design has been used internally in the VP-1 and VP-2 fiber bundles for the VIRUS-P survey. This design is shown in Figure 2.

An alternate design in development at McDonald Observatory uses the concept of a kinematic mount for locating the IFU head to the IFU mount plate. Three ball-studs are attached to the IFU mount plate and three V-grooves are created on the IFU head using dowel pins. Each of the three ball-studs is received by the V-grooves, forming a kinematic interface. The motivation behind this design is two-fold: unlike the cylindrical plug and receptacle design, machine tolerances do not contribute to repeatability of IFU position. In addition, this design is not susceptible to binding. Permanent magnets are utilized for axial holding force. This design is illustrated in Figure 3. The two designs will be analyzed for relative merit in positioning accuracy and repeatability for equal machine tolerances.

The conduit which protects the fiber bundles must terminate at the fiber head. In order to provide adequate strain relief, the conduit must be rigidly secured to the IFU head and the fibers must be protected from any burs or sharp edges at the conduit termination.

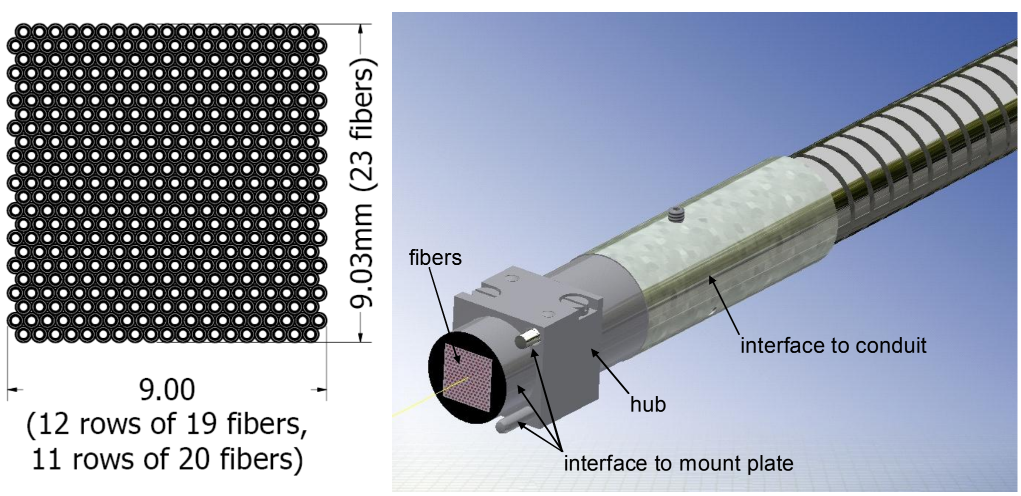


Fig. 2. Layout of active cores of 448 fibers in VIRUS VP-4 IFU head, as seen looking into the unit [photon's eye view]. There are 12 rows of 19 fibers and 11 rows of 20 fibers. The fill factor is close to one-third , with 450 μm pitch. The black circles denote the 450 μm OD of capillary tubes [if used to set up the matrix]. The IFU is about 8.8 mm [50 arcsec on the upgraded HET] on a side.

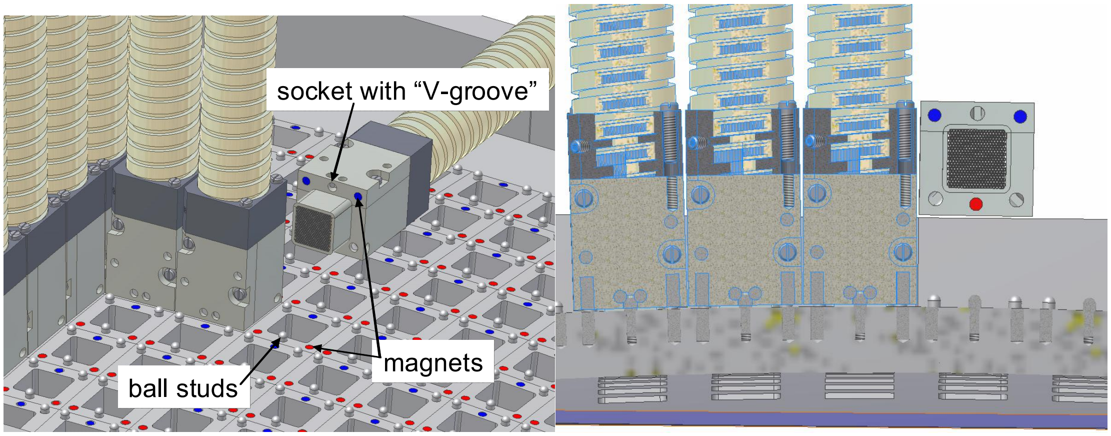


Fig. 3. The input end of the IFU mounts to the focal surface by means of a plate machined to match the curvature of the focal surface at the top of the wide field corrector.

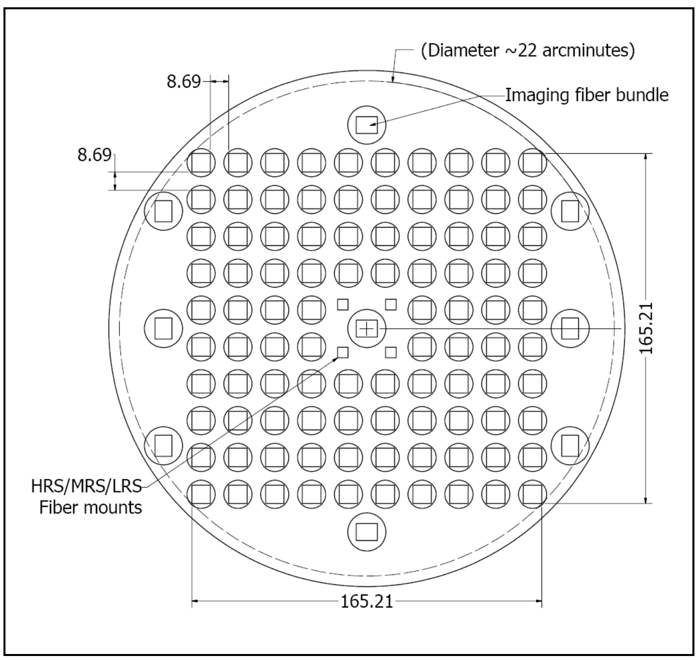
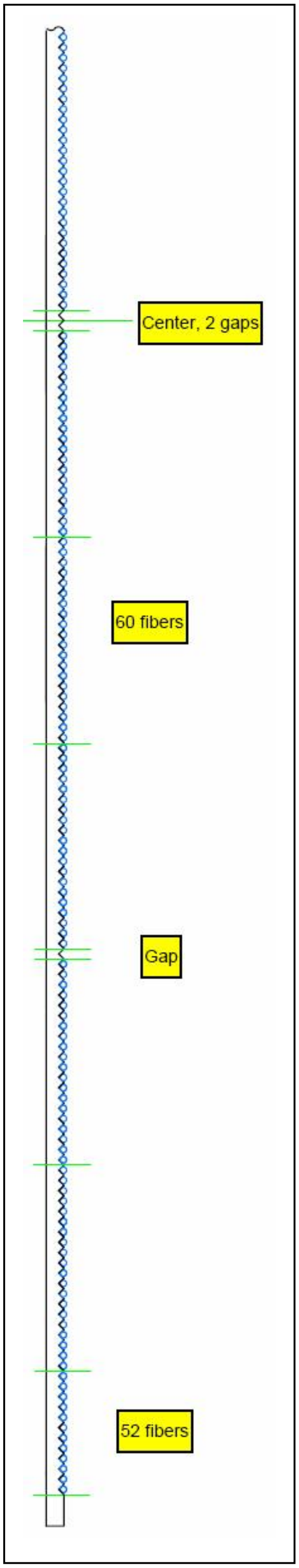


Fig. 4. The mount plate locates and supports 96 IFU heads at the focal surface. The 10 x 10 grid will also accommodate fibers for current HET instruments.

The IFU mount plate will locate and support the 96 IFU input heads at the telescope focal surface. In addition to the VIRUS IFU heads, the mount plate will also support nine imaging fiber bundles and fibers for the HRS, MRS, and LRS instruments. The VIRUS IFU input heads are arranged in a 10 x 10 rectangular grid, with the four central locations removed to accommodate current HET instruments. The separation distance between each IFU head was designed as a one-quarter fill factor. This enables a full image to be produced through four pointings on the sky. The layout of the IFU mount plate is illustrated in Figure 4.

2.3 The IFU Output and Breakout Box

The output end of the IFU is composed of two linear arrays of 224 fibers, each of which form the entry slits for a pair of VIRUS instruments [see Figures 5 and 6]. Rather than bifurcating into conduits near the termination point, which would pose a risk of exceeding the allowed bend radius of the fibers, the IFU conduit enters a "breakout box," where the fibers exit and form a service loop to create slack, as they route to the two spectrometers. Slit heads, which contain each fiber array, are mounted to the box and are aligned with mounting pins to the front-end of the spectrometer optics train. The service loop contained within the box is long enough to prevent any possible over-tensioning of the fibers and to allow the fibers to flow in and out of the conduits due to thermal expansion differences between the PVC outer layer of the conduit. This particular design consideration is thought to be important since the thermal expansion of PVC can be as much as 130 times that of silica fibers. While the protective steel winding inside the conduit will have some mitigating influence on the total lengthening of the conduit due to temperature change, provision for this feature of the design is taken into account, even though the actual values have yet to be determined.



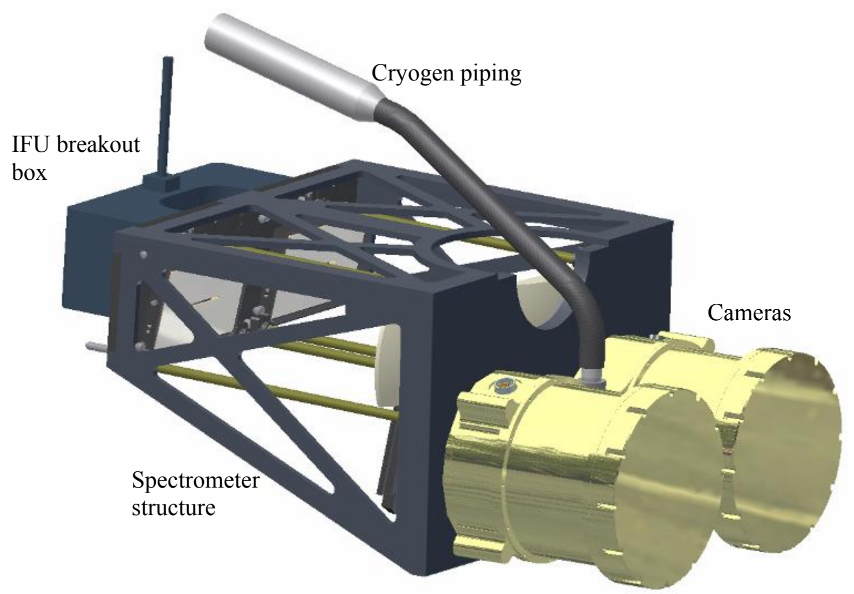


Fig. 5 [above]. The IFU enters the VIRUS spectrometers through a breakout box shown on the left end of the assembled pair. The spectrometer optics are mounted in a unitized structure with cameras mounted on the right end of the assembly. Cryogens for cooling the detectors are piped in through the plumbing shown connected between the camera assemblies.

Fig. 6 [left]. Layout of fibers at slit input to a single spectrograph. The slit substrate is monolithic, with grooves for the fibers. Half the layout is shown, with symmetry about the indicated center line. Half the fibers in Figure 2 go to each spectrograph. The pitch from fiber center to center in the grooves is 352 microns corresponding to an angular pitch of 0.048 degrees. The gaps between fibers are also on the same pitch [one fiber is missing each time]. The order of the fibers arrayed in the slit will be random with respect to the layout in Figure 2, within a slit and between the two spectrographs in a unit.

3. THE SUPPORT SYSTEM

3.1 Focal Surface Strain Relief

The first strain relief of the VIRUS IFU fiber bundles is located on the focal plane assembly, located at the top of PFIP, as shown in Figure 7. This structure serves to isolate the fibers at the focal surface from motions of the tracker and PFIP, which includes the Rho stage, hexapod, and instrument changer. This strain relief structure also supports the mass of the fibers running from the focal surface to the next strain relief, located near the base of the hexapod [about 4.0 meters]. The strain relief structure was designed to also position the fiber bundles away from the focal plane assembly to provide space for and access to other instrumentation. Another consideration of the strain relief structure design was installation and maintenance requirements of

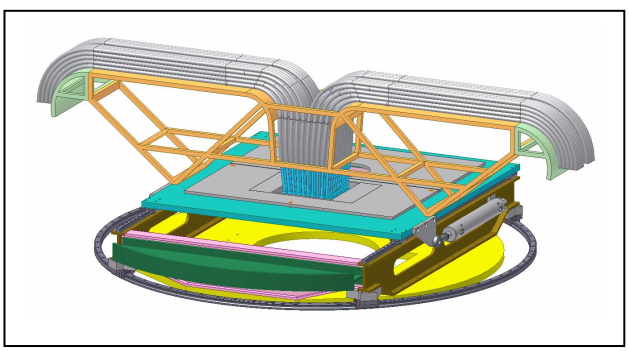


Fig. 7. The focal surface strain relief supports the mass of the fiber bundle from the top of the PFIP to the fiber carriage. The fibers must have enough service loop to accommodate +/- 20 degrees rotation of the Rho stage.

the individual IFUs. At present, the failure and replacement of individual fibers is considered low probability, and therefore priority has been placed on reducing fiber length at the cost of individual fiber accessibility. Nevertheless, installation is expected to proceed with one IFU at a time. Therefore the strain relief assembly and IFU mount plate are designed to enable IFUs to be individually secured.

3.2 IFU Docking for Maintenance of PFIP

Time constraints for the HETDEX upgrade, and uptime requirements of HET operations, necessitate an efficient means of attaching and detaching HETDEX's 96 IFUs for PFIP installation or removal, and also permit adequate clearance and protection for the fiber optic bundles during major maintenance operations. Substantial time would be required for serial installation and removal of each individual IFU, which is further complicated by conditions imposed when working atop the telescope structure. Therefore, all fiber optic inputs to the PFIP will have provisions for installation and removal as a unified assembly, while retaining the ability to extract and replace an individual IFU. A preliminary concept for this procedure has been developed, and is illustrated in Figure 8.

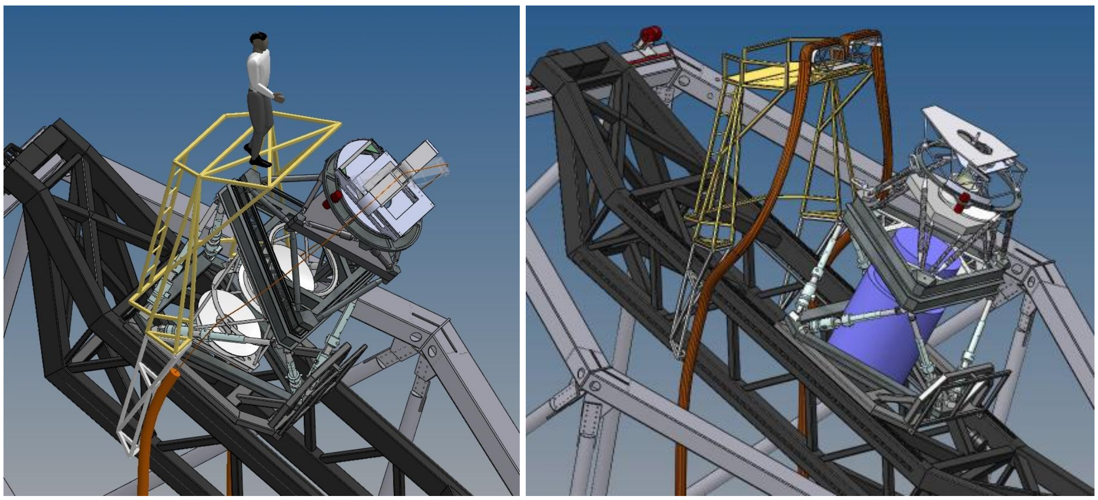


Fig. 8. The 96 IFUs will be routed in two bundles of 48 each, to the right and left side of the HET tracker. They are independently supported by carriages riding on linear bearings attached to either side of the tracker bridge, and they may be coupled and decoupled to the PFIP Y-axis drive stage. A temporary work platform [shown supporting a human figure] interfaces with these components. The fiber/focal plane assembly is lifted by means of an overhead hoist. Once the focal plane assembly is removed and secured to the work platform, the fiber carriage can be fixed in place on the tracker bridge and released from the tracker carriage and PFIP assembly, thereby freeing the fiber optic support system of all connections to the rest of the tracker.

A temporary work platform, which attaches by means of pins to the fiber carriage, will be raised from ground level and mated to components of the fiber optic support system. Its purpose is to fulfill two primary requirements: 1) provide a stable work surface for technicians and enable access to the top of the PFIP, and 2) possess attachment features for securing and supporting the IFU bundle and focal plane subassembly once it is removed from the PFIP. A platform that can be positioned within close proximity of the PFIP is essential so that the focal plane assembly can be off-loaded to nearby support without introducing the need for excess fiber length. However, this is counter to the mode where technicians require the greatest access and working clearance for PFIP ingress or egress from the tracker. To resolve this conflict, the fiber optic support system is designed such that it is an independent sub-unit of the HET's tracker system, enabling the service procedure detailed in Figure 8. The focal plane assembly and fiber optic support system remains a single coherent unit fixed atop the tracker bridge structure, yet the tracker carriage is free to move to a different position along the tracker's Y-axis, which enables maintenance on the PFIP.

A modular approach generates many benefits to the fiber optic support system design, and has been incorporated into Concepts Two and Three. In addition to facilitating maintenance and commissioning, actual performance of the HET when outfitted for DEX may be improved. Points of direct interaction between the fiber optic support system and instrument platform are held to a minimum so that the two may be separated quickly. This design is also driven by the intent to minimize mechanical disturbance transmitted through the fiber optic cabling. Wind disturbances and dynamic loads imparted to the majority of the fiber length and mass are terminated in the fiber carriage supports before reaching the PFIP, and these are coupled to the most rigid element of the tracker--the tracker bridge structure. There exists a strong possibility that the fiber support carriage attachments to the tracker bridge and linear drive stage will include additional isolation and damping measures if it is discovered that transmitted forces from the IFU impact the performance of the tracker. Finally, the long-term adaptability of the fiber optic support system is improved through modular design. Individual components may be upgraded for capacity, modified for new science requirements, or decommissioned and removed upon completion of HETDEX without interfering with normal operation of the HET telescope.

3.3 Concept Two

Concept Two places VIRUS at the upper hex of the HET structure. Several methods and concepts for transferring the fibers from VIRUS to the tracker were considered. Ultimately, a hinged carrier arm concept afforded the most benefit in a feasible design [Figure 9].

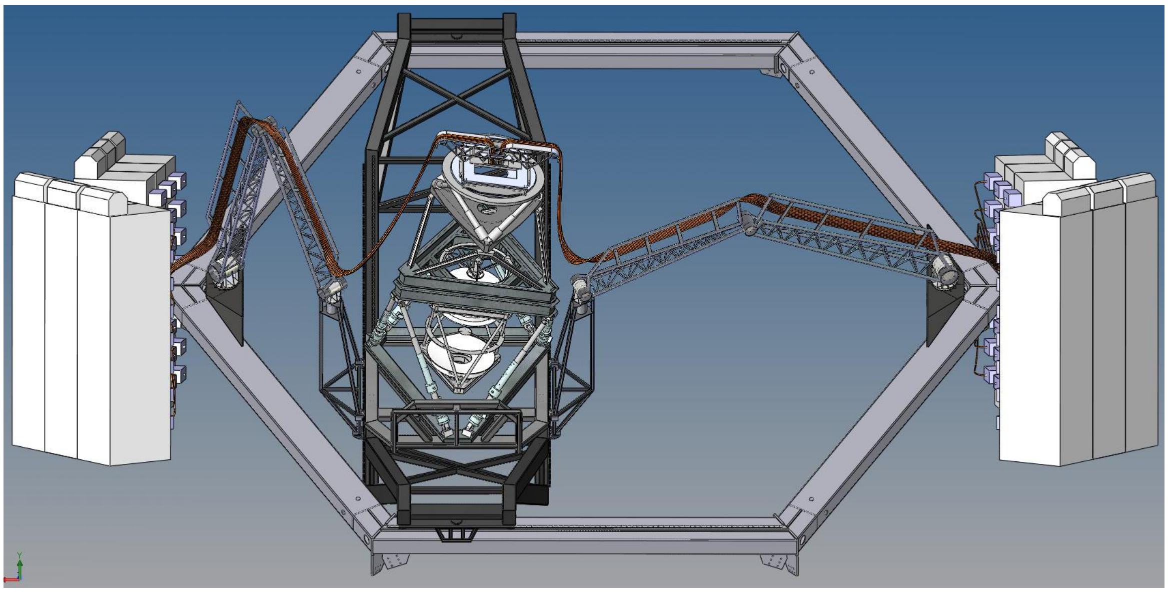


Fig. 9. In Concept Two VIRUS is mounted within enclosures on either side of the upper hex. An articulating IFU support arm spans the distance between each VIRUS array and the tracker. The IFUs are attached to the arms in a vertical "ribbon cable" type arrangement which provides the minimum overall length by allowing the same bend radius for each IFU and minimizing friction between them. An additional benefit is that the minimum profile of the "ribbon" is presented on the primary mirror, thus reducing obscuration.

First and foremost, fiber length can be held to a minimum by placing VIRUS in close proximity to the PFIP. Concept Two produces a fiber length in the vicinity of 15 m. The IFUs are arranged in a vertical column of either 2 x 24 or 4 x 12, and routed down the length of the hinged carrier arms. This "ribbon cable" arrangement minimizes the primary mirror area obscured by the IFUs when viewed from the optical axis of the primary mirror. Additionally, the "ribbon cable" geometry has the unique feature of permitting equal length and equal radius bends at each hinge location, a key characteristic for optimizing fiber length [Figure 10].

Aerodynamic considerations are of particular importance to Concept Two due to the location of the IFUs in relation to the HET dome enclosure. The dome's aperture produces the dominant wind flow currents within the enclosure, and mounting VIRUS at the same elevation means the IFUs and fiber optic support system will be placed in this region of highest velocity wind current, thereby complicating the task of minimizing the effects of wind disturbances to the tracker. The "ribbon cable" arrangement of the IFUs presents challenges, specifically with regard to the magnitude of forces imparted on the fiber optic support system by high winds, which are believed to be minimally attenuated as they enter the dome aperture. Vertically stacking IFUs effectively generates greater frontal area and correspondingly higher forces compared to more densely packed arrangements. Each pair of IFUs must be spaced such that an air gap is left between them to mitigate their collective "sail" effect. Worst case wind loads were modeled using computational fluid dynamics software and deemed to be manageable, though design for aerodynamic performance has not been optimized.

An investigation to measure and characterize wind at the top of the telescope, and determine its power spectra, is currently underway.

The hinged carrier arms provide the highest level of mechanical support and protection to the IFUs, constraining them over the majority of their length. IFU axes and ranges of motion, and their corresponding bend locations, are pre-determined and restricted by the kinematics of the fiber optic support system. The design of the handling arms must take the kinematics and dynamics of the tracker into account, as their geometry can significantly affect the static and dynamic loads that the fiber optic support system imposes on the tracker. Preliminary feasibility studies of mechanical loads were investigated using rigid body dynamic modeling software. Although manageable, a potentially complex engineering solution may be required to cancel a percentage of the mass and force interactions introduced between the tracker and fiber carrier arms as they appear in this concept.

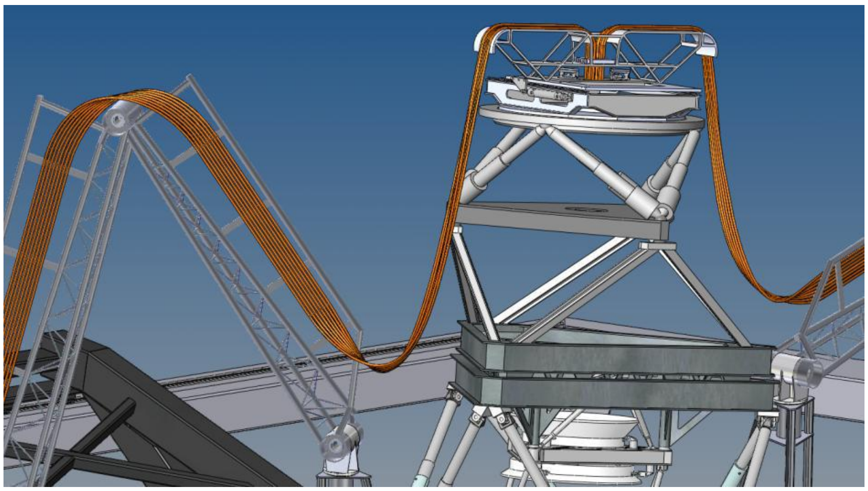


Fig. 10. IFU ribbon cable arrangement concept and equal length / radius bend geometry.

The greatest engineering challenges of Concept Two deal with the logistics of placing VIRUS at an elevated location on the HET. Significant structural support is required between the 28,000 kg VIRUS mass and the foundation of the HET. The VIRUS mass is also concentrated forward of the azimuth bearing and therefore not distributed equally on the HET's bearing system. The additional mass of the required structure exceeds the capacity of the HET azimuth drive system, necessitating an upgrade. In addition to the modifications required for VIRUS, the fiber optic support system itself requires modification to the upper hex to create the mount for the support system at the upper hexagon. Structural enhancements are also required to support additional forces on the hexagon. Modifications such as these, which involve welding and multiple lift operations, will require more time in the HETDEX upgrade installation schedule. Concept Two also includes accessibility compromises. All installation and maintenance operations, both on VIRUS and the fiber optic support system, must be executed at high elevation [about 17.5 meters] on the HET. Transporting personnel and equipment to this region safely presents both technical and time constraint challenges, and will likely require constructing a service platform [an industrial service elevator] for access to the VIRUS array and the new tracker.

3.4 Concept Three

Concept Three positions the VIRUS spectrographs near the base of the HET structure [see Figure 11], eliminating many of the maintenance and logistic challenges posed by Concept Two. Locating the two VIRUS arrays on opposite sides of the HET base allows them to be positioned symmetrically about the azimuth bearing center, equally distributing their mass and inertia. Simplified structural engineering eliminates sufficient mass such that the existing azimuth drive system may be reused without modification. Overall, the components of the fiber optic support system have been simplified in Concept Three and system mass is subsequently reduced. Eliminating the fiber optic carrier arms frees the tracker system of kinematic hardware interactions that magnify mechanical loads on the tracker bridge and drive stages.

The most obvious implication of Concept Three is an additional 5 m of fiber length, resulting in an estimated average IFU length of 20 m. The IFUs transition off the PFIP to support carriages as described previously, but nearly 50% of their total length [8 m] will hang suspended between a point on the tracker and a point on the lower telescope structure. Each of the two bundles of 48 IFUs will therefore have approximately 95 kg of their total mass suspended between these two points. At present, it is assumed that the IFU conduits will have adequate strength to self-support this mass, along with a small mass contribution from fiber optic support system guiding and tethering hardware. Unlike the conduit, which has the benefit of strain relief attachments at multiple locations, the IFU fibers are essentially free-hanging within the conduit over the majority of their length. The 16.25 m height differential will place each fiber in a constant state of self-weighted tension. Though this condition is not fundamentally problematic, the bulk behavior of 448 fibers within a single conduit is not well known for this configuration. Conditions could arise through modes of friction, excessive tension and pressure induced by bulk fiber mass interaction and entanglement between discrete fibers, which result in much higher actual stresses than might be expected. Accelerated life testing will be required to replicate real fiber behavior for this application. Details of this test follow in later sections of this paper.

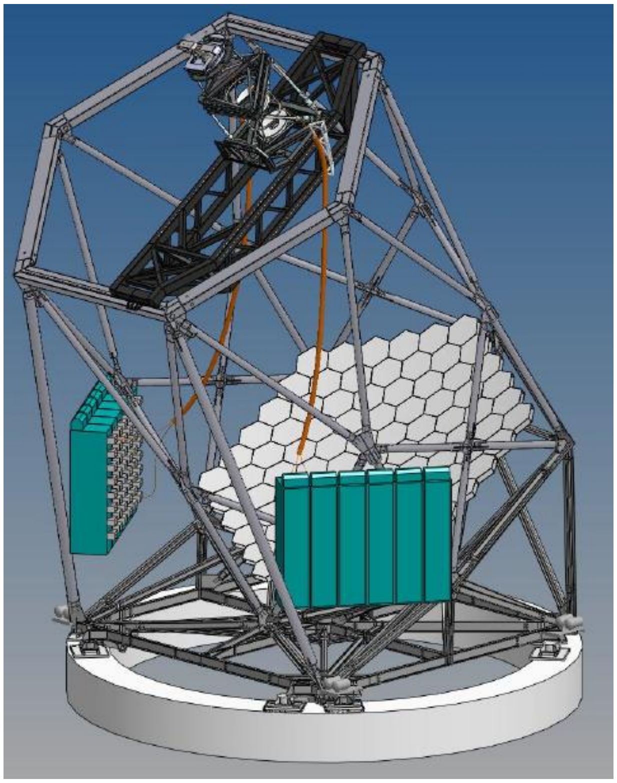


Fig. 11. Concept Three positions the VIRUS array near the base of the telescope. The average fiber length required is about 20 meters. The 28,000 kg mass of VIRUS is supported directly on the HET pier and is coupled to the telescope structure for stability. There is no appreciable loss of performance in the stiffness of the telescope structure or its azimuth drive system.

On a macro level, the IFU bundle must be evaluated for obscuration and aerodynamic profile. Unlike Concept Three, the IFUs are arranged in a densely packed circular arrangement. The outside diameter of a 48 IFU bundle will measure between 100 and 150 mm, depending on packing factor and conduit diameter. Due to vignetting caused by the support arms for the ribbon arrangement and each concept's similar path length over the primary mirror, obscuration of Concept Three is expected to be comparable, if not less than that of Concept Two. Additional IFU length implies a larger aerodynamic profile and net force induced by winds. However, environmental conditions are expected to be more favorable for Concept Three. The majority of IFU length resides below dome aperture level where air currents are less severe, and may be controlled to a greater degree by opening and closing the HET's louvered enclosure. In spite of this advantage, this execution of the fiber optic support system fundamentally exerts less control and restraint over the IFUs. An ancillary component of full scale accelerated life testing will be to verify frequencies and loads that the suspended IFU bundle will generate in dynamic scenarios, as well as develop effective methods for mitigating their propagation into the tracker.

4. FIBER STRESS AND FRD TESTING

The bulk behavior of 448 fibers contained in each IFU, and the impact this will have on the throughput and longevity of the individual fibers, is considered a risk to the HETDEX project. There is specific interest in whether the bulk dynamics of the fibers under self-weight tension and translations will impose stresses on individual fibers, which increase focal ratio degradation [FRD], or produce cracks or fiber breakage over time. Currently an experiment is being set up at The University of Texas Center for Electromechanics, in which a 20 meter IFU will be put through accelerated life testing to resolve these questions. The test set-up will include all of the physical and dynamic characteristics of the Concept Three IFU. The experiment will be sufficiently automated to measure throughput from individual fibers over the duration of the test.

We have already constructed a fiber optic test bench to conduct transmission and FRD tests on prototype IFUs for VIRUS-P. Comprehensive FRD testing of both IFUs has been completed [Murphy et al, 2008 SPIE] at 365 nm, 400 nm and 600 nm where we find a weak wavelength dependence on FRD [Figure 13]. Our FRD measurements are conducted with a science grade CCD and a novel method of measuring a fiber's output f-ratio. This method is simple in concept and execution, and has proven precise enough to quantify the small amount of FRD expected from our relatively fast input beam of F/3.65. Our FRD tests involve imaging the far field of an individual fiber at multiple positions from the output fiber end. IDL routines are in place to calculate the output f-ratio to 2% accuracy. Each set of two positions returns an estimate of the output f-ratio. Multiple camera positions give multiple estimates of the output f-ratio, allowing us to quantify the random errors in our measurements [Figure 12]. This is an improvement on the common method of testing FRD which involves output apertures to estimate the output f-ratio. This method requires precise knowledge of the position of the output fiber end, particularly for fast input beams.

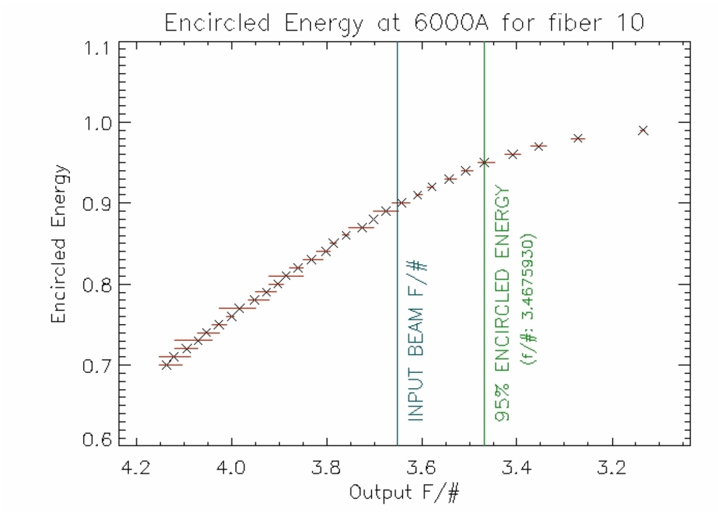
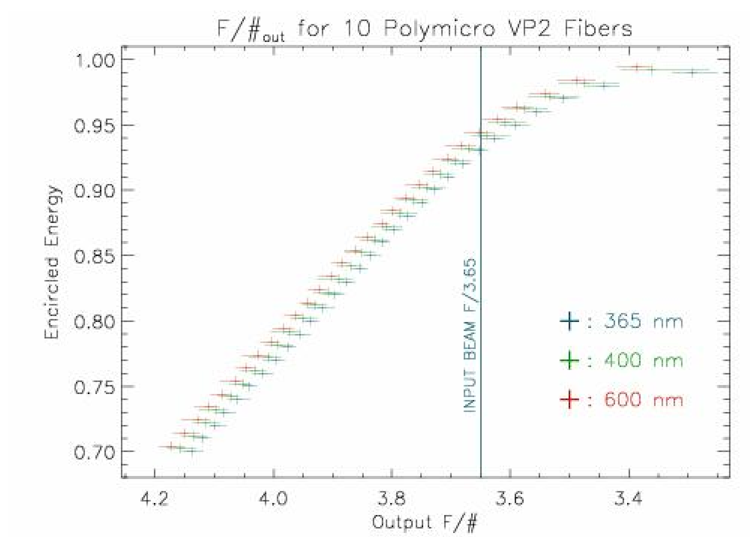


Fig. 12. An example of a typical FRD measurement for one fiber. The F/3.65 input beam is shown in blue and the 95% encircled energy limit and corresponding output F/# in green. The 'X's denote the weighted average of the six estimates of the output F/# as described in the text. The red error bars show the scatter of those estimates.

In order to understand the influence of flexure on FRD, both in the immediate [due to the degree of bending] and in the long term [due to fatigue and micro-fractures] we are planning a series of tests on a new fiber bundle constructed for the purposes of flexure testing. First, comprehensive tests of FRD and transmission will be made on the bundle to quantify its initial state. The fiber bundle will then be put through a series of hang and flexure tests. After these tests are completed we will repeat the tests on the same fibers. This will allow us to quantify the long-term effects flexure has on the change in the degree of FRD for a given fiber address, and address the question of whether repeated flexure permanently degrades the focal ratio of fibers.

The second aspect of our planned tests is a monitoring program intended to measure the degree of instantaneous FRD due to bending, axial stress due to the weight of the fibers and other internal stresses due to the fiber bundle sheathing. To measure this type of FRD some degree of automation is required. A simple approach is to monitor the output of an individual fiber at one camera position. By testing the fiber initially with the camera step method described above, deviations in the diameter of the output spot can be bootstrapped to this initial measurement and an estimate of FRD made. After the initial set-up and measurement of FRD for a set of fibers is made, the bundle can be taken through a series of flexures and stresses, with a CCD camera and software recording the far field image of the output spot. Upon completion of a series of tests, the FRD of that fiber will then be retested. By bookending a complete automated test of FRD with the camera step method, we will be able to collect a good set of data with minimal supervision. Then, by repeating this test on a number of fibers, we can begin to address the influence of the fiber bundling on FRD. This can be accomplished by comparisons of the laboratory tests [where the bundle is not

Fig. 13 [right]. The results of FRD tests conducted on 10 Polymicro fibers [length 15 m]. The tests were conducted at three wavelengths and show a weak yet clear trend for worse FRD at lower wavelengths. For visual clarity, the encircled energy estimate has been slightly offset for the three wavelengths shown. The symbols denote the weighted mean of ten different fibers, while the error bars reflect the scatter over all ten fibers tested. Note that this is different from the above figure, where the error bars reflect the scatter on one fiber.



stressed], the initial step tests [where the bundle is under tension, but not under flexure], and the automated flexure tests [where the bundle is both under tension and under a variety of bent and twisted positions]. As an individual fiber's position within the bundle is not known a priori, we can use the statistics gained from testing multiple fibers to understand how flexure and twisting of the fiber bundle influences FRD. As radial stress is a known source of FRD, it is important to explore a number of fibers in order to understand how different configurations of the fiber bundle affect FRD of individual fibers.

Currently, a test bench exists to make both the initial and final laboratory transmission and FRD measurements. Examples of the far field image of both the input and output spots and their radial profiles is shown in Figure 14. Note the presence of a central obscuration in the input spot and how this profile changes after passage through the fiber. This blurring effect is due to FRD. Also note the central obscuration in the input spot. This is included in our test set-up in order to understand the influence of the HET corrector central obstruction on FRD.

Our laboratory test bench was designed to allow for repeated tests at a wide range of wavelengths. Due to our interest in understanding both our transmission and FRD well into the blue [we can test wavelengths ranging between 337 nm and 600 nm] and to conduct these tests on a wide variety of fibers, the test bench was constructed with mirrors to both collimate and focus the beam. For our on-site flexure tests, a new and simplified version of the laboratory test bench will be constructed. By considering a single wavelength, we will not be hampered by the limits of chromatic aberration; thus, a pair of achromatic doublets and an aperture stop will be used to collimate the beam and set the input f-ratio. At the output end of the fiber bundle, a CCD camera mounted on a z-translation stage is all that is required. Once the output f-ratio is confirmed by the CCD step method, the camera can be left at the same location for the duration of the a round of tests. As FRD is independent of the brightness of the source, accurate measurements can be made spanning many hours and even days. Based on the extensive laboratory tests conducted to date, this simplified method will yield accuracy to within 5%.

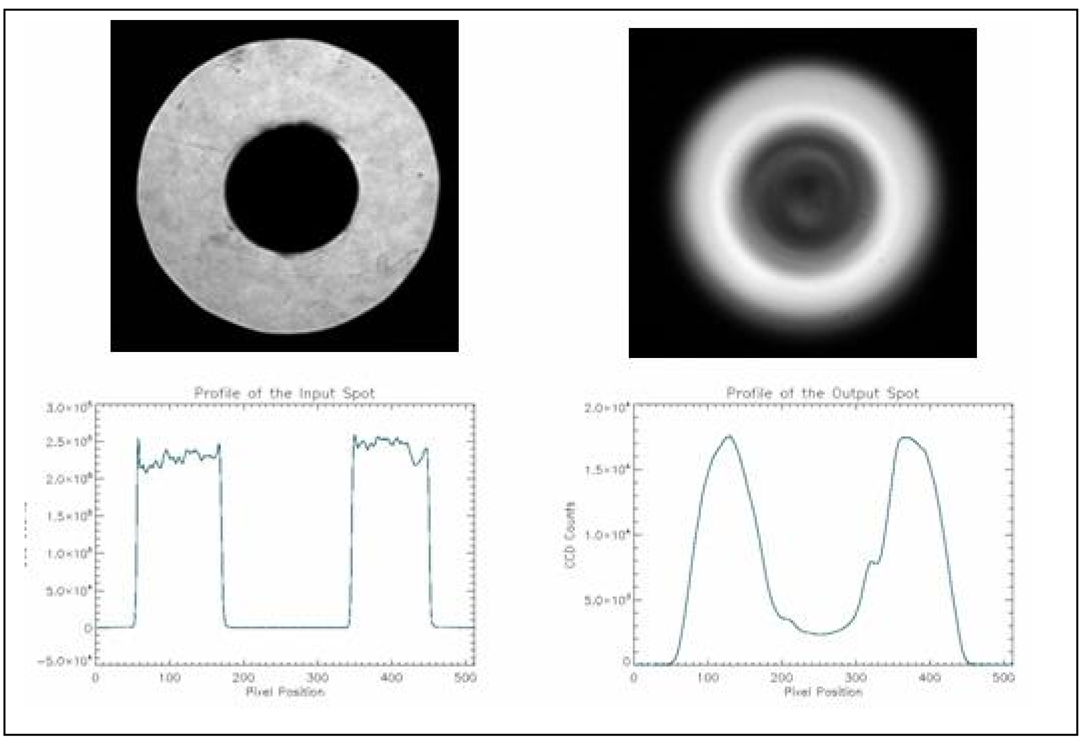


Fig. 14. An image and radial profile of both the input and output spot of our current fiber optic test bench. The central obscuration constitutes ~42% of the input spot diameter and mimics the secondary mirror of the HET. The effect of FRD can be seen in the shallower radial profile of the output spot.

5. SUMMARY

Support and articulation of 96 IFUs presents challenges to the overall design of the new tracker for HET, as well as new thinking about how to install and manage large numbers of optical fibers in the HET facility. An understanding of the short and long-term effects on the optical performance of 448 fibers within a single IFU, is vital to the success of the science mission, and presents serious but reasonable technical challenges. The sum of overall trades in the HETDEX program favors positioning the VIRUS array as shown in Concept 3 resulting in an average fiber length of less than 20 meters and a maximum height differential of 16.25 meters. With all other trades accepted as workable, the design and testing efforts currently planned will prove whether the concept design for the IFU and its support method, is sound, and if not, will expose any weaknesses that require refinement or changes to the current design.

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