VIRUS: assembly, testing and performance of 33,000 fibres for HETDEX

Kelz, Andreas, Jahn, Thomas, Haynes, D., Hill, G., Lee, H., et al.

Andreas Kelz, Thomas Jahn, D. Haynes, G. J. Hill, H. Lee, J. D. Murphy, Justus Neumann, Harald Nicklas, M. Rutowska, C. Sandin, O. Streicher, S. Tuttle, M. Fabricius, S. M. Bauer, B. Vattiat, H. Anwand, R. Savage, "VIRUS: assembly, testing and performance of 33,000 fibres for HETDEX," Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 914775 (10 July 2014); doi: 10.1117/12.2056384

Event: SPIE Astronomical Telescopes + Instrumentation, 2014, Montréal, Quebec, Canada

VIRUS: assembly, testing and performance of 33,000 fibres for HETDEX

A. Kelz*[a], T. Jahn[a], D. Haynes[a], G. J. Hill[b], H. Lee[b], J. D. Murphy[b], J. Neumann[a], H. Nicklas[c],
M. Rutowska[a], C. Sandin[a], O. Streicher[a], S. Tuttle[b], M. Fabricius[d], S.M. Bauer[a], B. Vattiat[b],
H. Anwand[c], R. Savage[b]

[a]Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany;
[b]The University of Texas, McDonald Obs., 2515 Speedway C1402, Austin, TX, USA 78712-1206
[c]Institut für Astrophysik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany
[d]Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany

ABSTRACT

VIRUS is the visible, integral-field replicable unit spectrograph for the Hobby-Eberly-Telescope (HET) consisting of 75 integral-field-units that feed 150 spectrographs. The full VIRUS instrument features over 33,000 fibres, each projecting to 1.5 arcseconds diameter on sky, deployed at the prime focus of the upgraded 10m HET. The assembly and acceptance testing for all IFUs includes microscopic surface quality inspections, astrometry of fibre positions, relative throughput measurements, focal-ratio-degradation evaluation, and system acceptance using a VIRUS reference spectrograph to verify the image quality, spectral transmission, stability, or to detect any stray light issues.

Keywords: optical fibres, integral-field units, spectroscopy, test and metrology, HETDEX

1. INTRODUCTION

VIRUS is the visible, integral-field replicable unit spectrograph for the Hobby-Eberly-Telescope (HET) in Texas to conduct the Dark Energy Experiment (HETDEX [1]), with the aim to survey a 420 square degree area in the north Galactic cap. Essentially, HETDEX is a blind spectroscopic survey with an unprecedented field of view. Each exposure is expected to result in spectra of several hundred objects, mainly Lyman-alpha emitting galaxies in a volume of 9 cubic Gpc. The measured distribution of galaxies shall yield constraints on the expansion history of the Universe, and such on Dark Energy, at redshift epochs between 1.9 and 3.5.

As to be able to undertake such a large survey, the telescope is fitted with a new wide field corrector [2] to enable a field-of-view of 22 arcminutes. The HET is also upgraded with a new tracker at the prime focus, which houses the plug plate for an array of integral-field-units (IFUs). The full VIRUS instrument will feature over 33,000 fibres, each projecting to 1.5 arc sec diameter on sky. The fibre output is directed to a set of 150 spectrographs that record all the spectra simultaneously.

Altogether 75 IFUs with 448 optical fibres each are being constructed in a mini-series – partially at the responsible institute (AIP), partially by outsourcing and providing technology transfer to local enterprises. The overall assembly and acceptance testing for all IFUs is done at AIP and includes microscopic surface quality inspections, astrometry of fibre positions, relative throughput measurements, focal-ratio-degradation evaluation, and system acceptance using a VIRUS reference spectrograph to verify the image quality, spectral transmission, stability, or to detect any stray light issues.

The paper describes the dedicated test-benches and methodologies to evaluate this large number of optical fibres and discusses the achieved performance and accuracies. Also presented are the opto-mechanical layout of the VIRUS-IFUs and the precision mechanics to deploy the fibres accurately at the focal plane.

HETDEX and VIRUS are developed by an American-German consortium of 9 institutes, led by the University of Texas at Austin. AIP is responsible for developing the fibre-based integral-field-units for VIRUS.

*eMail: akelz@aip.de; www.aip.de

Ground-based and Airborne Instrumentation for Astronomy V, edited by
Suzanne K. Ramsay, Ian S. McLean, Hideki Takami, Proc. of SPIE Vol. 9147,
914775 · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2056384

2. THE VIRUS INSTRUMENT IN BRIEF

The overall VIRUS instrument is presented by Hill et al. [3]. The concept is based on a high degree of modularity. To accommodate the large number of spectra needed for the survey, the instrument is broken down into replicable units that can be purchased or manufactured economically in mini-series and assembled individually. This modularity also minimizes risks and allows to down-scale the instrument in case of limited budget, or to extend it even further at a later stage.

VIRUS consists of an array of 150 identical spectrographs [4] fed by optical fibre bundles. The spectrographs feature reflective collimators [5], a VPH grating [6] and a Schmidt camera system. The detectors are 2k × 2k CCDs with customized controllers. The spectrographs are mounted within two enclosures on opposite sides of the telescope main frame (see Fig. 1). As the HET does not move in elevation, the spectrographs are mounted invariant with respect to gravity.

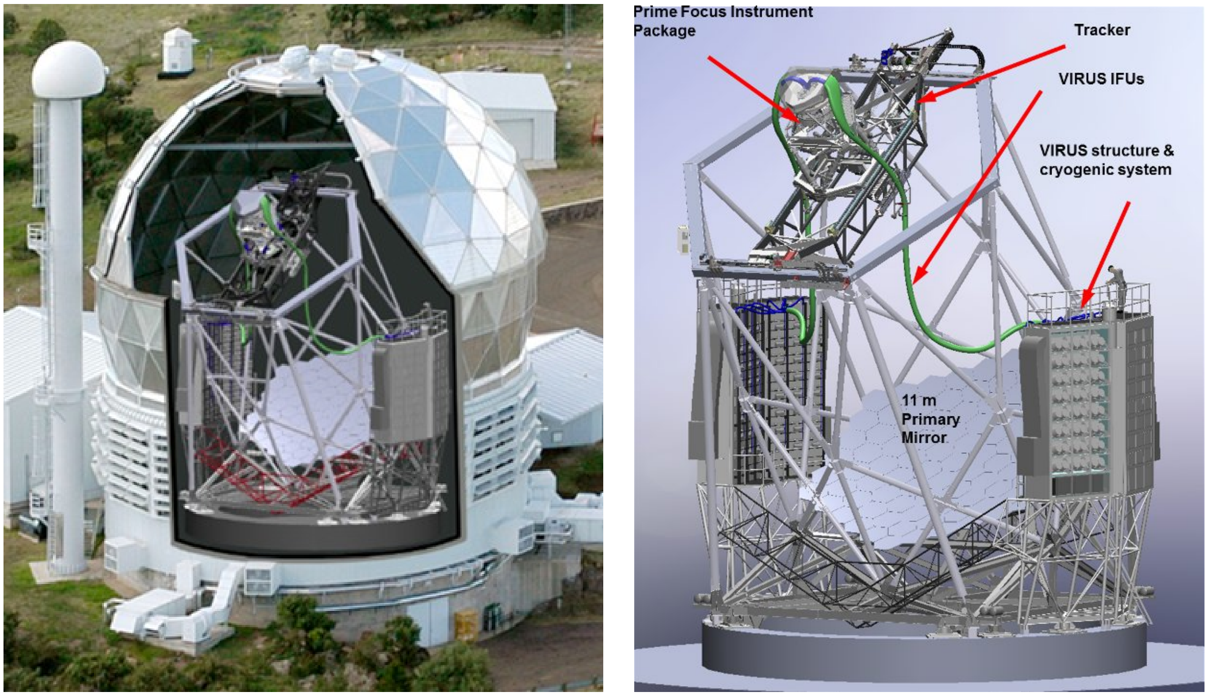


Figure 1. Animated views of the Hobby-Eberly Telescope and the (to be deployed) VIRUS instrument. At the prime focus, the light is picked up by the integral-field-units (IFUs) and guided in 20m long fibre bundles to the spectrographs, which are mounted beside the telescope structure.

The two main purposes of the Virus Integral-Field Units (VIFUs) are to guide the light from the HET focal plane to the spectrographs and to reformat the 2D-spatial sampling into a linear slit configuration. The challenges are to do this with highest efficiency, precision and stability, given that the fibre run is around 20 meters in length and that the IFU head is subjected to movement caused by the HET tracker located at the prime focus.

3. VIRUS-IFU DESIGN

The VIRUS-IFUs (VIFUs) consists of the input head, the cable conduit and the double-slit unit. The fibres are inserted in precision mechanics at both ends to ensure low tolerances for both the fibre lateral positions and their pointing angles. Fig. 2 gives an overview of the VIFU design and the various parts.

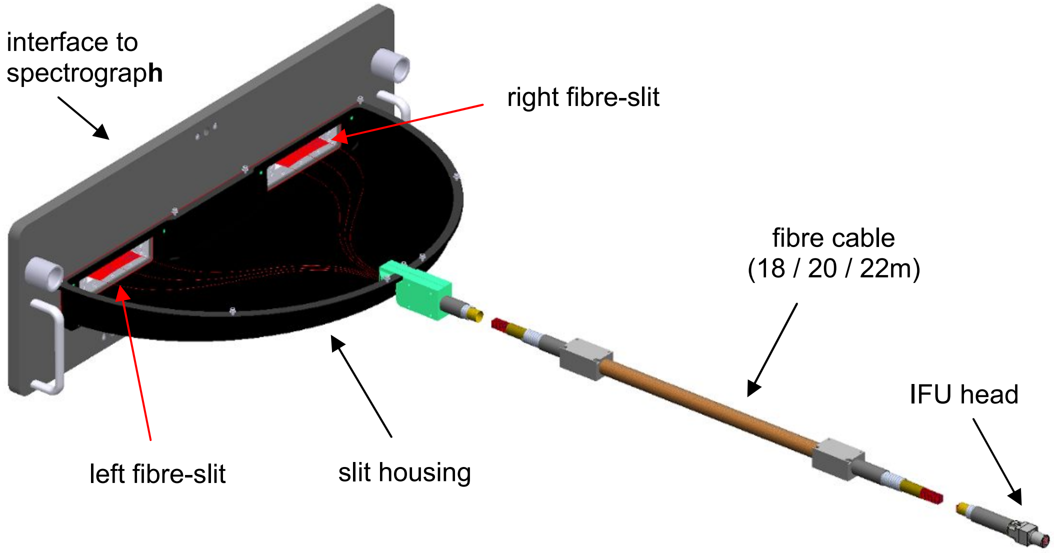


Figure 2. CAD view of the VIRUS fibre bundle design. The bundles are 18m, 20m, or 22m long. A single IFU head forms the entrance, while at the output the fibres fan out to form two slits.

3.1 VIFU input head design

The fibre layout at the VIFU head is based on a hexagonal grid with a sparse packing. The distances between fibre cores in the grid are chosen in a way that a 3-dither exposure fills the total IFU area. Altogether 448 fibres are placed in an IFU, arranged in 23 rows of alternating 19 and 20 fibres respectively (see Fig. 3). The optical design includes a plano-convex lens in front of the IFU head, which features an anti-reflective coating at its outer surface.

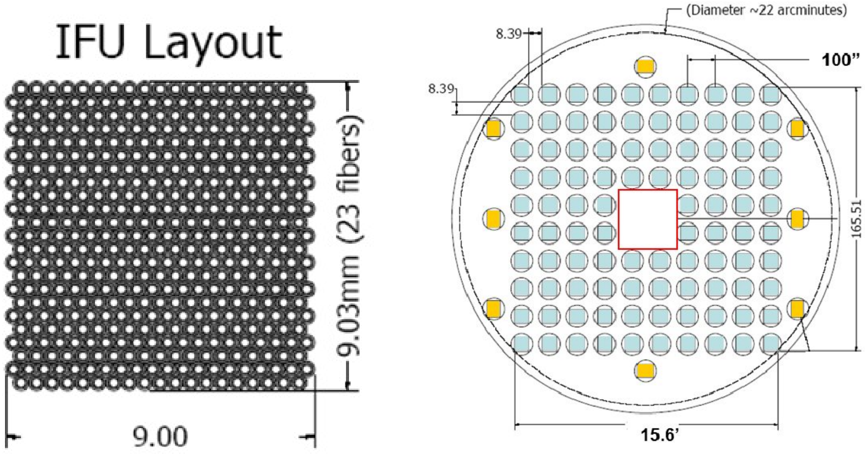


Figure 3. The VIRUS-IFU layout. Left: layout of the sparse hexagonal packed 448 fibres in 23 rows. The physical size is 9 × 9 mm which corresponds to 50 × 50 arcseconds on the sky. Right: the grid arrangement of up to 96 IFUs, covering 15.6 arcminutes on sky at the upgraded HET prime focus. The central square is being left empty of VIFUs, to allow the placement of fibre-feeds for the existing Low- and High-Resolution Spectrographs (LRS and HRS).

Altogether up to 75 IFUs are foreseen at the focal plane and are placed in a sophisticated plug plate (see Fig. 9) with tight mechanical tolerances (+/- 5 microns) with respect to location and rotation. The packing fraction of the IFUs is one quarter, so that a 4-dither exposure fills the 20 arcminute wide field of view.

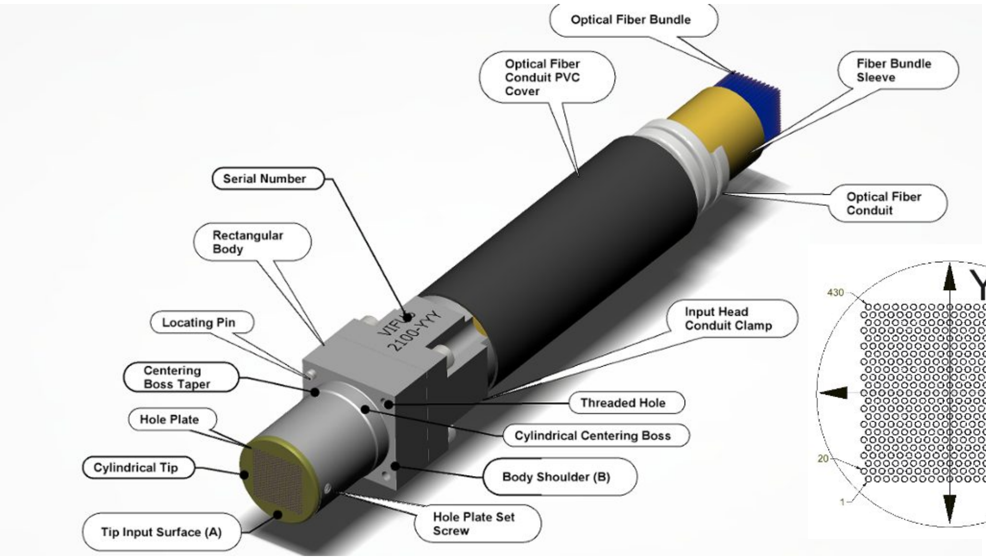


Figure 4. The VIFU input head design: the IFU consists of a precision hole-plate to accommodate 448 fibres in a sparse hexagonal packing with a 1/3 fill factor. The head mechanics feature a cylindrical centering boss and a location pin to accurately position each IFU-head at the plug plate at the focal plane.

3.2 VIFU slit design

At the exit, the IFU bundle splits into two fibre slits containing 224 fibres each, which feed two parallel VIRUS spectrographs. The design of the spectrograph optics requires an angular pitch between fibres of 0.048 degrees and a convex slit geometry with curvature of 419 mm (see Fig. 5). The fibre slit is optically coupled to a cylindrical lens that simultaneously serves as the first element of the collimator optics. Interlaid within the fibre-slit are deliberate gaps, to assist spectra tracing and the estimation of the fibre point-spread-function (PSF) at the detector.

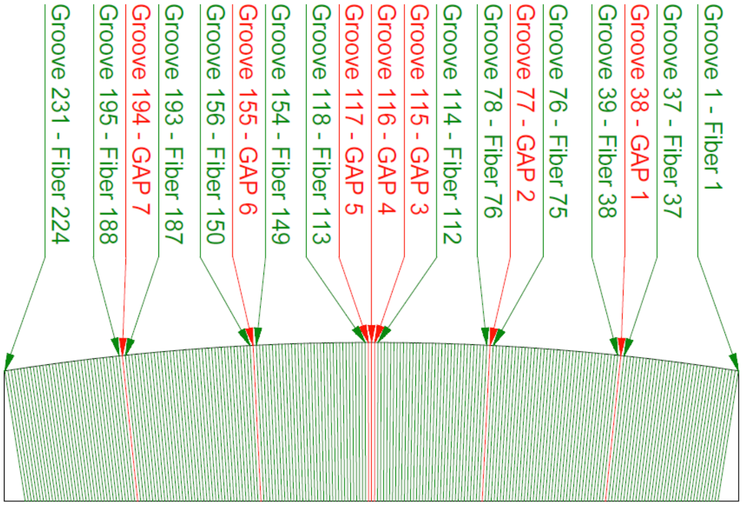


Figure 5. Layout of the v-groove block of a single slit that is populated with 224 fibres and 7 intentional gaps. As required by the optical design of the spectrograph, the fibres are positioned with separation of 350 microns, an angular pitch of 0.048 degrees, and the overall fibre slit is convex with a radius of 419mm.

3.3 VIFU cable design

Depending on the location of the spectrograph on the telescope structure, fibre cable lengths between 18m and 22m are required. The cable conduits provide protection against outside pressure, pull or bending, while ensuring a stress-free movement of the fibres with little friction. The cable consists of three layers (Fig 6): an inner Kevlar sleeve that protects the bare fibres from sharp edges and provides a low-friction surface, and an outer conduit made from aluminum plus PVC for the mechanical protection and sufficient stiffness against stretch and sharp bends.

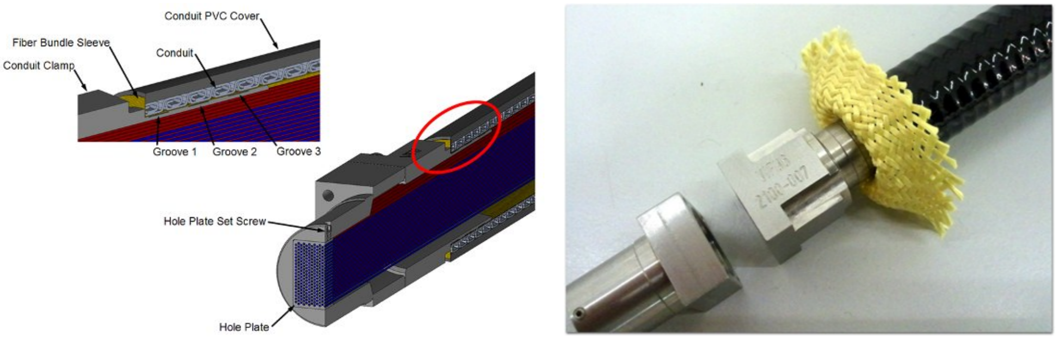


Figure 6. Left: cut-view of the input head and its connection to the conduit. Right: image of the conduit connector to the IFU head assembly, with part of the inner Kevlar sleeve extending outside.

4. IFU MANUFACTURE

4.1 Mechanical parts

The most critical mechanical parts of the VIFUs are the input and output mounts (Fig. 7) for the fibres and their interfaces to the IFU mount plate and the spectrographs. In order to ensure accurate and repeatable fibre positions at the focal plane, the fibres are inserted in a precision hole-mask. The individual holes in the mask have an inner diameter of 330 microns (+0, -5 microns), i.e. they are slightly oversized with respect to the fibre outer diameter, which is 316 (+/- 3) microns. The fibres are glued with a low-shrinkage 2-component epoxy (Epo-Tek 301/2) into the hole-mask. The end surface of the IFU-head is polished flat and smooth. After surface inspection and acceptance testing (see below) a plano-convex lens is optically bounded in front of the IFU head using a UV-curing optical adhesive (NOA 61).

At the slit side, the fibres are placed in V-grooves that were drawn into a stainless steel block. The V-grooves set the correct fibre pitch and angular pointing. An additional lid on the top ensures that the fibres lay correctly in the grooves and do not bend side or upwards. Again the fibres are glued into the mechanical block using the 2-component epoxy Epo-Tek 301/2. An interesting challenge was to find a method to polish the convex fibre-slit without introducing errors into its geometry (given curvature in x- and flat, perpendicular surface in y-direction), and simultaneously to ensure that the fibres are polished without a preferential direction. To achieve this, a polish tool was built, that combines an automated movement in y (to ensure the perpendicularity) with a manual movement in x to follow the curvature. The actual polish is done using an oversized polish block with the negative curvature. Polish papers with grain sizes ranging from 30 to 0.3 microns and a liquid finish polish is applied.

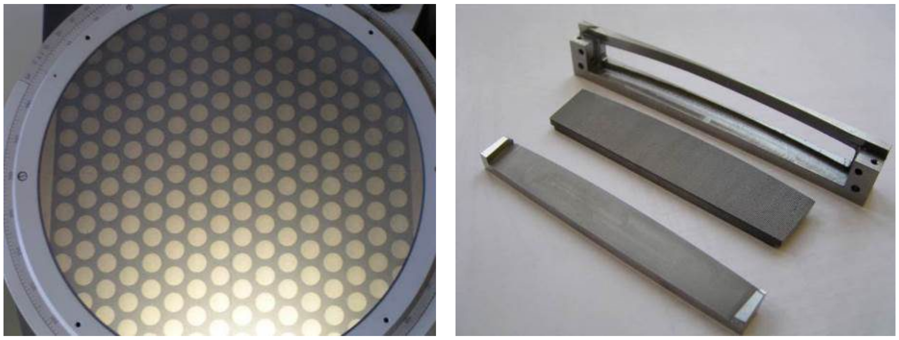


Figure 7. Left: magnified view of a precision hole-mask that positions the fibres at the IFU input. Right: the mechanical parts for the fibre slit: a v-groove block with lid and the mount for the cylindrical lens, all made from stainless steel.

4.2 VIFU Assembly

At first, IFU prototypes (called VIRUS-P [7]) were designed and assembled at AIP, which included different manufacturing approaches, such as fibre stacking vs. hole-masks, and different conduit options. After evaluation of the prototype performances, the final design was fixed and the serial production started. AIP transferred knowledge and technology to fibre companies for the industrial production and provided the in-house manufactured precision parts.

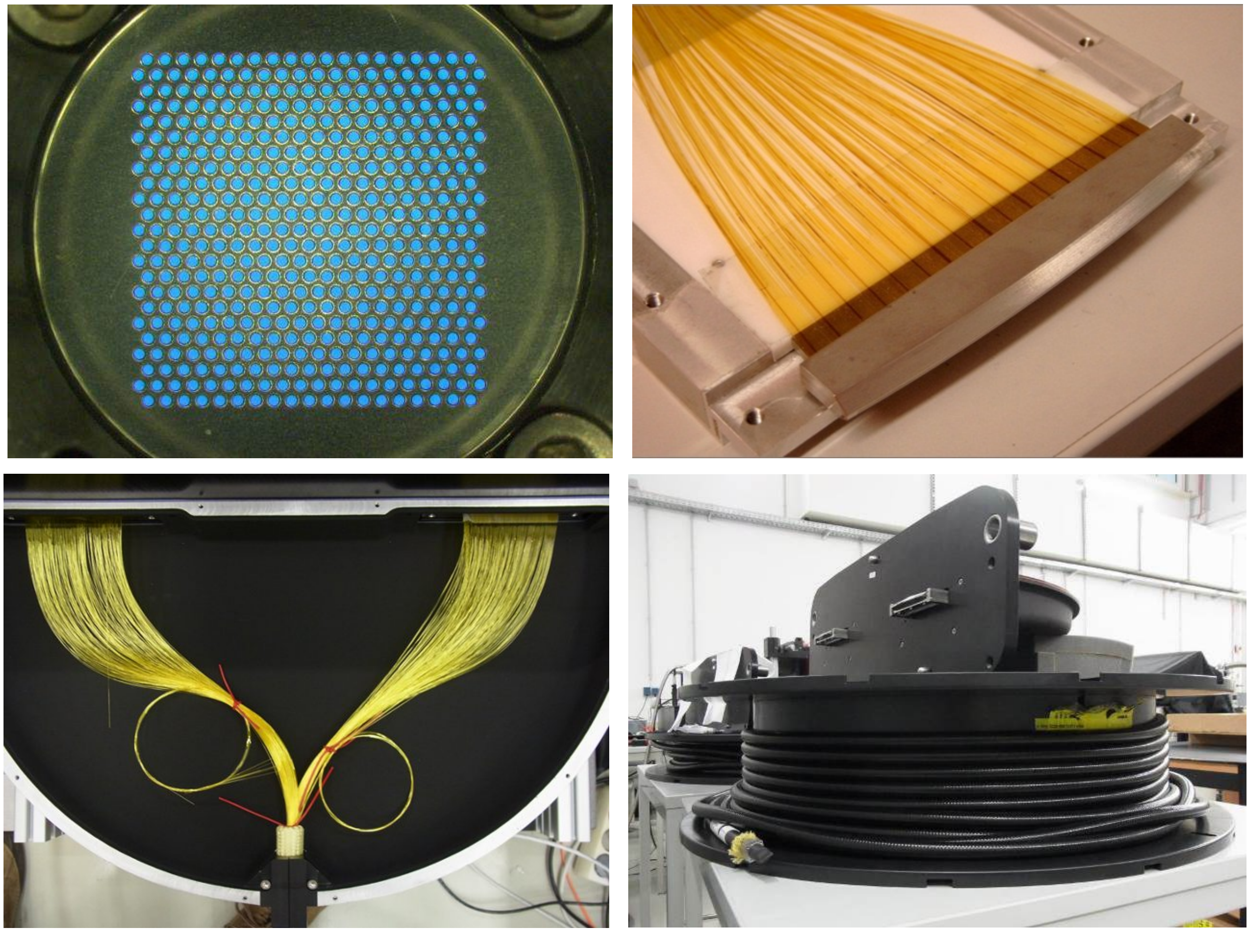


Figure 8. Impressions from the IFU assembly: front view of the IFU head with back-illuminated fibres (top left); a completed fibre-slit with convex curvature (top right); view of the open slit housing, illustrating the bifurcation of the bundle into two slits and some spare fibres in loops (lower left); a completed, rolled-up fibre bundle with assembled double-slit interface (lower right).

In brief, the order of assembly was as follows: i) fibres were laid out and cut to the required length; ii) 450 fibres were inserted into a Kevlar sleeve and the conduit; iii) the hole mask was filled with the input ends of the fibres; iv) the input head was assembled, the fibres glued, and polished; v) the fibre output ends were mapped and allocated into the corresponding v-grooves; vi) the fibre slits were glued and polished; vii) the fibre slits were integrated into enclosures; viii) the output lenses were mounted behind the slit assemblies; ix) the input lens was bounded in front of the IFU head. Some steps of the assembly process are shown in Figures 8 and 9.

4.3 The VIRUS-P IFU

Parallel to the assembly of the standard VIRUS IFUs, a slightly altered fibre bundle was built for the VENGA survey (the VIRUS-P Exploration of Nearby Galaxies [8]). This VIRUS-P IFU at the 2.7m Harlan-J-Smith Telescope at McDonald Observatory is currently the largest field-of-view (FOV) IFU in the world. It has 246 optical fibres (each 4.3" in diameter) which sample a 1.7′ × 1.7′ field with a 1/3 filling factor. Three dither exposures provide continuous coverage of the FOV, yielding spectra of 738 independent spatial resolution elements per pointing.

Figure 9. Left: a first configuration of 3 × 3 IFUs mounted in a preliminary plug plate, featuring over 4000 fibres. Right: The complex and precise Input Head Mount Plate (IHMP, produced at IAG) allows to accurately position up to 96 VIRUS IFUs in a rectangular grid with a ¼ fill factor and with spherical curvature that matches the telescope focal plane.

5. IFU ACCEPTANCE TESTING

5.1 Surface and geometry inspection

Given the importance of the quality of the fibre termination, all end surfaces are inspected visually. A digital microscope (Keyence VHX 2000) was used to detect and document any scratches, fibre breakages, and to evaluate the surface polish quality. A few examples of good and bad fibre end surfaces are shown in Fig. 10. Using calibrated measuring tools, the microscope also allows a verification of the head and slit geometry, such as fibre pitches and distances. Finally, the correct mapping of the fibres from IFU head to slit is checked visually.

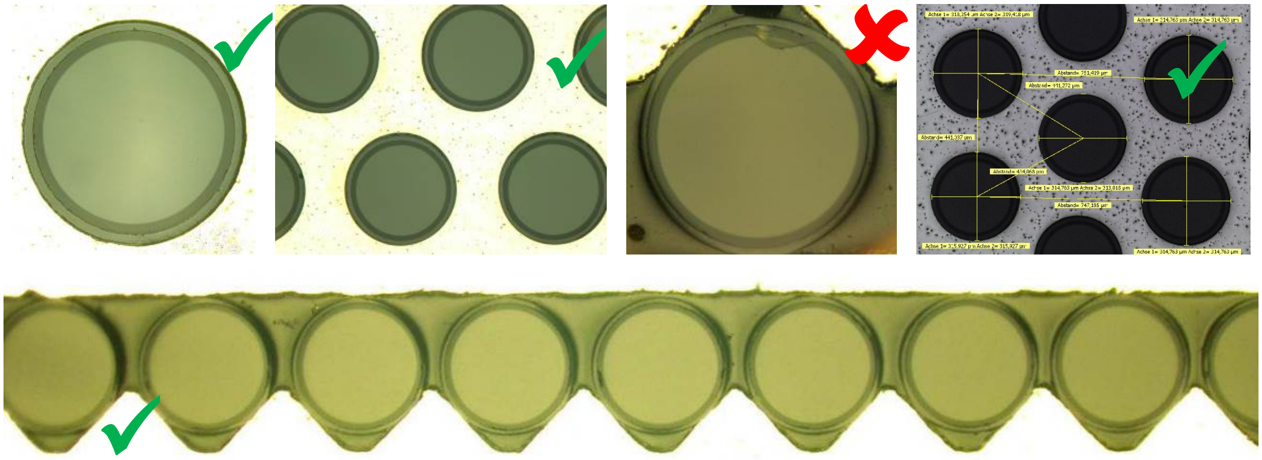
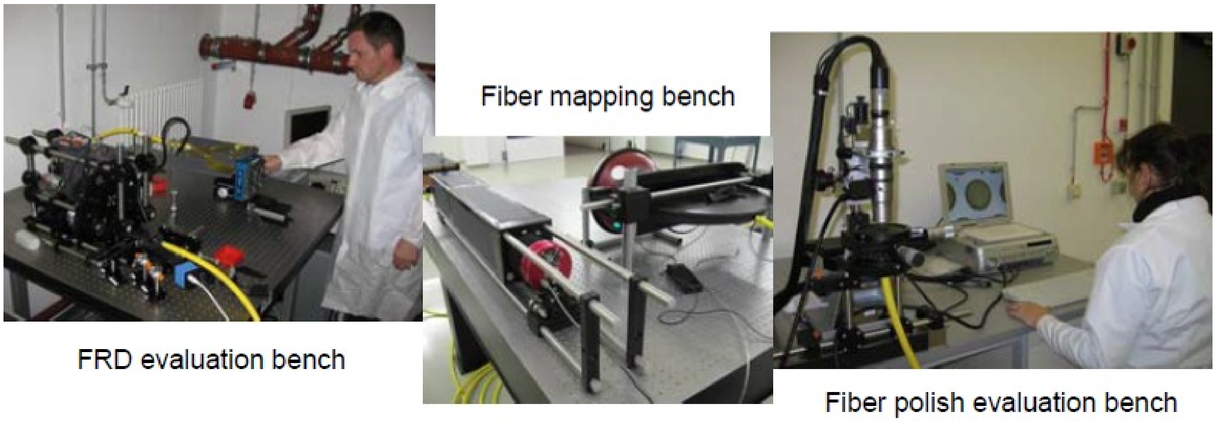


Figure 10. Examples of fibre ends (top row: IFU head, lower rows: fibre slit) with good and imperfect surface finish (e.g. dirt, scratches, breakages, etc.). The inspection, metrology and documentation are done using a digital microscope with magnification ranging from ×100 to ×400.

5.2 Metrology and relative transmission

A test-bench (Fig. 11) was setup to measure the positions of all 448 fibres inside the IFU-head. Essentially, the bench features a high-quality aberration-free optics that is used to re-image the IFU head onto a technical CCD. The fibre cable under test is backside-illuminated at the slit and a high-resolution image of the fibre head is recorded showing all of 448 fibre cores. The images are processed to determine the centroids of all fibre PSFs and their fluxes within a given aperture. Typically, the fibre positions can be recovered to 3-4 microns. This astrometry information is used in the software, to map the real fibre grid onto the sky.



Fiber mapping bench

FRD evaluation bench

Fiber polish evaluation bench

Figure 11. Left: the FRD test bench features a collimator-camera system with various apertures to inject a light cone with given F-number into the fibre. A technical CCD records the far-field beam at the output end. Middle: the mapping or metrology test bench consists of an integrating sphere to illuminate the fibre slit and a camera system to re-image the IFU head onto a technical CCD. Right: the fibre end surface quality is checked with a digital microscope.

5.3 Focal Ratio Degradation (FRD) testing

The FRD test bench at AIP consists of a collimator-camera system that projects the image of a pinhole onto the fibre. Different sized apertures can be selected at the collimated light section to set a given F-number (NA) for the injected light cone. The aperture wheel also contains the option to include a secondary obstruction, as present in the telescope. At the slit end, the far-field fibre output cone is projected onto a CCD system (Apogee with 2k × 2k chip).

For each FRD measurement, seven CCD frames are taken at different distances between fibre and CCD. The resulting images are background subtracted and the spot size for a given amount of encircled energy is calculated. The ratio between aperture size and distance determines the output F-number of the beam.

The results on focal ratio degradation and transmission in VIRUS-P optical fibres were already reported in [9], where the influence of wavelength, end immersion, fibre type and length on both FRD and transmission was explored. Later, an accelerated life time test of a VIRUS bundle was done to study the influence of motion and stress on optical fibres [10]. Both studies show that the F/3.65 input beam is not degraded by FRD to any faster than the required F/3.35.

While the absolute calculation of FRD is tricky and highly depends on background light and level of encircled energy, the aim of the current measurement is to spot *relative* fibre degradation inside the overall bundle. The target is to identify any fibres that show a decreased performance, which may be caused by the assembly procedure (such as introduced stress from gluing, pulling, or bending). Some sample FRD data for a VIRUS bundle are given in the plot below.

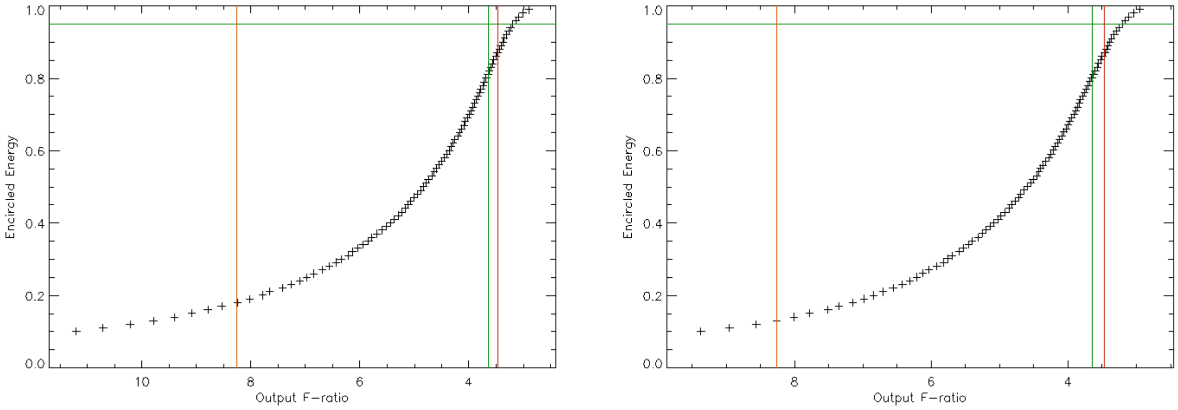


Figure 12. Examples for bad FRD results using an input beam with f-ratio of 3.65, either with a free aperture (left), or with a central obscuration (right). The aim is to obtain 95% encircled energy (horizontal line) at an output f-ration of 3.45 (vertical line) or slower.

5.4 System Acceptance testing

The final acceptance test is done with the fibre cable connected to a VIRUS spectrograph [4], (Fig 13). An illumination unit is used that provides both a flat field across the IFU and feeds the light with the proper F-number into the fibres. Because a single IFU feeds two spectrographs, two detector frames need to be recorded for each IFU.

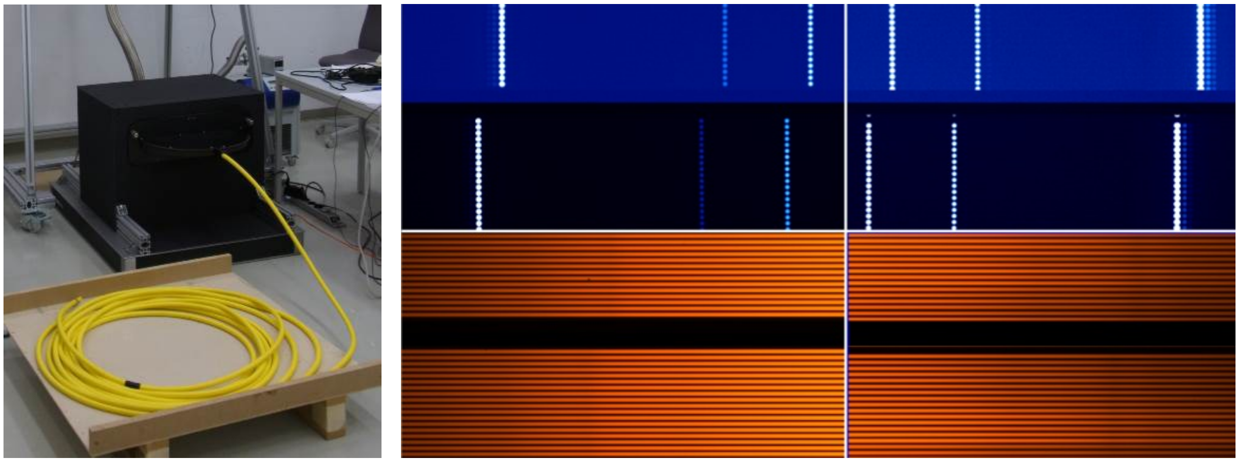


Figure 13. Left: all fibre-IFUs (yellow bundle) are tested for acceptance using a standard VIRUS spectrograph (black box) with two nitrogen-cooled detector systems. Right: Section of two raw frames obtained with the spectrograph with Hg-arc exposure (top part) and Halogen white light (lower part). The spatial slit direction is vertical, the spectral direction is horizontal.

The standard test series includes bias and dark frames, a white light flat, and a mercury arc exposure (Fig. 14). The white light flats result in continuum spectra that are used for the spectral tracing and the fibre-to-fibre throughput calculation. The arc frames are needed for the wavelength calibration and to determine the image quality using selected emission line spots across the chip.

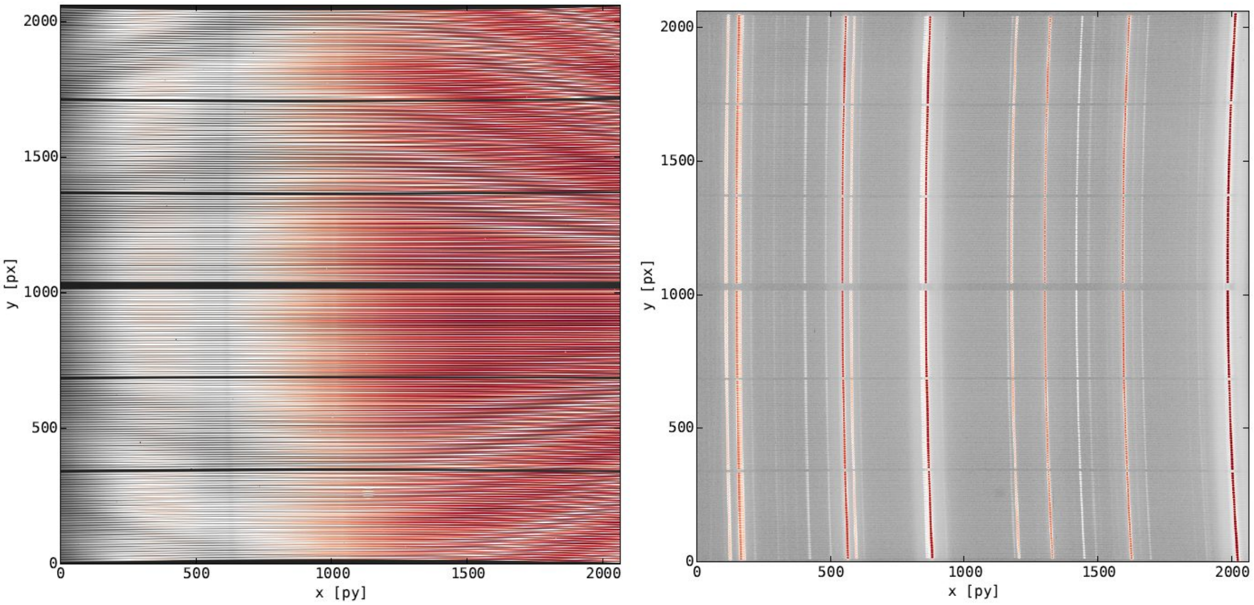


Figure 14. Examples of raw flat (left) and an arc frame (right). The dispersion axis is horizontal, while the vertical axis contains the 224 fibre-spectra. A Halogen lamp plus blue LED is used for the continuum spectra (left), while a HgCd spectral lamp provides the emission lines (right) in the fixed wavelength region between 350-550nm.

6. PERFORMANCE

The performance of the IFUs is measured with respect to relative throughput (Fig. 15), FRD (Fig. 12), metrology, and image quality (Fig. 16 & 17). Examples of results are presented in the following figures.

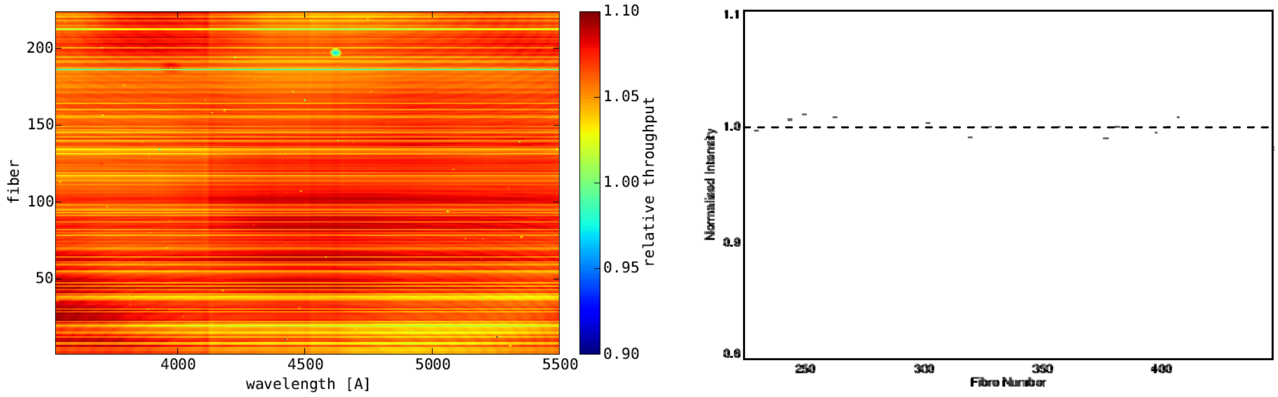


Figure 15. Left: Example of 224 extracted fibre fluxes, normalized at each wavelength to the mean flux. The color scale indicates the relative throughput from fibre to fibre. Right: Typical plot of the normalized fibre intensity across one slit. The scatter is around 3%.

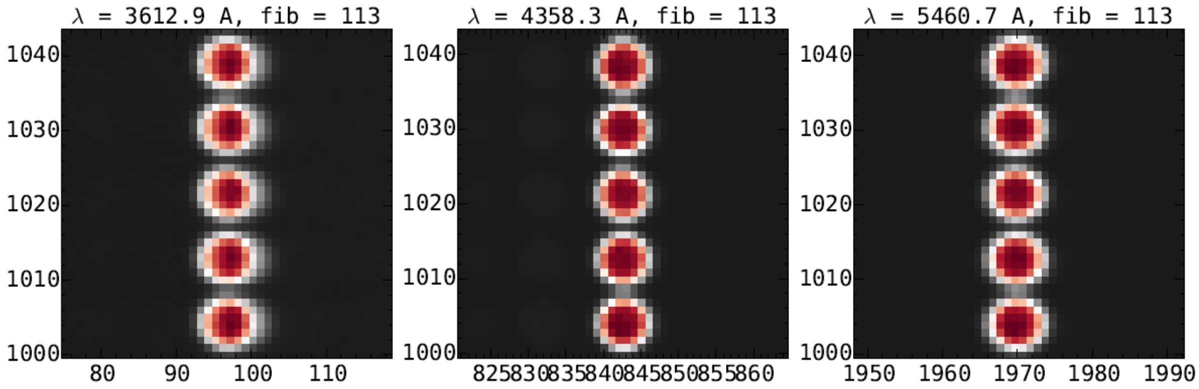


Figure 16. A section (of 50 × 50 pixel) from a raw arc frame, centered around three Hg-emission spots (at 361, 436, 546 nm). The spots are used to determine the PSF and to evaluate the image quality across the detector – both in spectral as well as in spatial direction. The color scale is arbitrary in linear stretch.

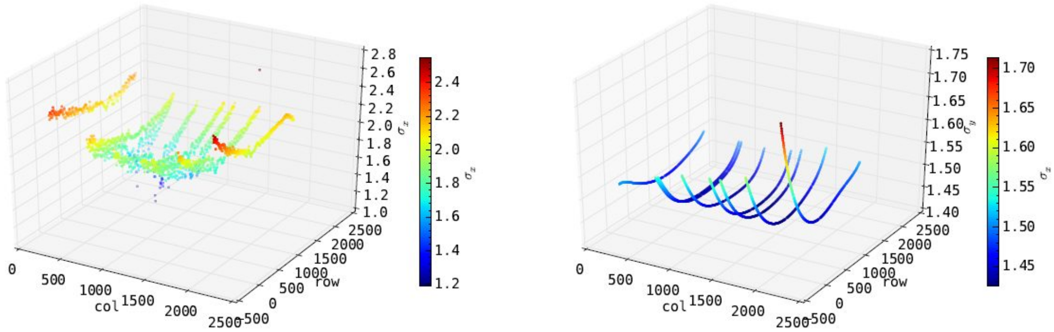


Figure 17. PSF sizes in pixel across the detector (with 2000 rows × 2000 columns). Left: PSF in spectral direction using seven emission lines; Right: PSF in spatial direction using seven different fibres. The PSF is best in the middle of the chip and the central wavelength region, but increasing towards the edges.

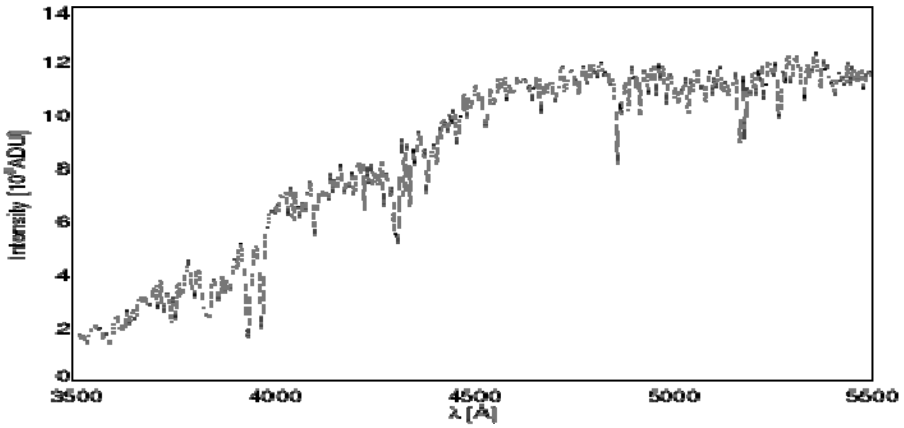


Figure 18. As a quick on-sky demonstration, a daylight sky spectrum was taken with the VIRUS equipment in the lab. As the spectrum is not flux calibrated it still contains the instrumental response of IFU, spectrograph and detector.

7. SUMMARY

For the VIRUS instrument, optical fibre-IFUs were developed and tested. By now, 50 out of 75 bundles have been manufactured and a subset tested. The average rate of broken fibres is less than 1 fibre (out of 448 fibres per IFU). The relative fibre throughput seems highly uniform with a scatter of around 3% rms. The position accuracy of the fibre placement (< 10 microns) and the FRD degradation (< 10%) are within the required specification.

ACKNOWLEDGEMENTS

HETDEX is run by the University of Texas at Austin McDonald Observatory and Department of Astronomy with participation from the Ludwig-Maximilians-Universität München, Max-Planck-Institut für Extraterrestriche-Physik (MPE), Leibniz-Institut für Astrophysik Potsdam (AIP), Texas A&M University, Pennsylvania State University, Institut für Astrophysik Göttingen (IAG), University of Oxford and Max-Planck-Institut für Astrophysik (MPA). In addition to Institutional support, HETDEX is funded by the National Science Foundation (grant AST-0926815), the State of Texas, the US Air Force (AFRL FA9451-04-2-0355), by the Texas Norman Hackerman Advanced Research Program under grants 003658-0005-2006 and 003658-0295-2007, and by generous support from private individuals and foundations. AIP and IAG gratefully acknowledge the institutional funding provided by their state and federal governments.

REFERENCES

[1] Hill, G.J., Gebhardt, K., Komatsu, E., Drory, N., MacQueen, P.J., Adams, J.A., Blanc, G.A., Koehler, R., Rafal, Roth, M.M., Kelz, A., Grupp, F., Murphy, J., Palunas, P., Gronwall, C., Ciardullo, R., Bender, R., Hopp, U., and Schneider, D.P., "The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX): Description and Early Pilot Survey Results," ASP Conf. Series 399, 115 (2008)

[2] Hill, G.J., Drory, N., Good, J., Lee, H., Vattiat, B.L., Kriel, H., Bryant, R., Elliot, L., Landiau, M., Leck, R., Perry, D., Ramsey, J., Savage, R., Damm, G., Fowler, J., Gebhardt, K., MacQueen, P.J., Martin, J., Ramsey, L.W., Shetrone, M., Schroeder, E., Cornell, M.E., Booth, J.A. and Walter Moriera, W., "Deployment of the Hobby-Eberly Telescope Wide Field Upgrade," Proc. SPIE 9145, 5 (2014)

[3] Hill, G.J., Tuttle, S.E., Drory, N., Lee, H., Vattiat, B.L., DePoy, D.L., Marshall, J.L., Kelz, A., Haynes, D., Fabricius, M., Gebhardt, K., Allen, R.D., Blanc, G., Chonis, T.S., Cornell, M.E., Dalton, G., Good, J., Jahn, T., Kriel, H., Landriau, M., MacQueen, P.J., Murphy, J.D., Prochaska, T., Nicklas, H., Ramsey, J., Roth, M.M., Savage, R. and Snigula, J., "VIRUS: production and deployment of a massively replicated fibre integral field spectrograph for the upgraded Hobby-Eberly Telescope," Proc. SPIE 9147, 25 (2014)

[4] Tuttle, S.E., Hill, G.J., Lee, H., Vattiat, B.L., Noyola, E., Drory, N., Cornell, M.E., Peterson, T., Chonis, T.S., Allen, R.D., Dalton, G.B., DePoy, D.L., Edmonston, R.D., Fabricius, M.H., Kelz, A., Haynes, D.M., Landriau, M., Lesser, M.P., Leach, R.W., Marshall, J.L., Murphy, J.D., Perry, D., Prochaska, T., Ramsey, J., Savage, R., "The construction, alignment, and installation of the VIRUS spectrograph," Proc. SPIE 9147, 26 (2014)

[5] Marshall, J. L., DePoy, D. L., Prochaska, T., Allen, R. D., Williams, P., Rheault, J. P., Li, T., Nagasawa, D. Q., Akers, C., Baker, D., Boster, E., Campbell, C., Cook, E., Elder, A., Gary, A., Glover, J., James, M., Martin, E., Meador, W., Mondrik, N., Rodriguez-Patino, M., Villanueva, Jr., S., Hill, G. J., Tuttle, S., Vattiat, B., Lee, H., Chonis, T. S., Dalton, G., Tacon, M., "VIRUS instrument collimator assembly," Proc. SPIE 9147, 143 (2014)

[6] Chonis, T. S., Frantz, A., Hill, G. J., Clemens, J. C., Lee, H., Adams, J. J., Marshall, J. L., DePoy, D. L., and Prochaska, T., "Mass production of volume phase holographic gratings for the VIRUS spectrograph array," Proc. SPIE 9151, 53 (2014)

[7] Kelz, A., Bauer, S. M., Grupp, F., Hill, G. J., Popow, E., Palunas, P., Roth, M. M., MacQueen, P. J. and Tripphahn, U., "Prototype development of the integral-field unit for VIRUS," Proc. SPIE 6273, 121 (2006).

[8] Blanc, G. A., Gebhardt, K., et al., "The VIRUS-P Exploration of Nearby Galaxies (VENGA): Survey Design and First Results," ASP Conference Series 432, 180 (2010)

[9] Murphy, J. D., MacQueen, P. J. Hill, G. J., Grupp, F. Kelz, A. Palunas, P. Roth, M. and Fry, A., "Focal ratio degradation and transmission in VIRUS-P optical fibers," Proc. SPIE 7018, 92 (2008)

[10] Murphy, J. D., Hill, G. J., MacQueen, P. J., et al., "The influence of motion and stress on optical fibers," Proc. SPIE 8446, 5 (2012)