VIRUS: a massively-replicated integral-field spectrograph for HET

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ABSTRACT

We present the design of, and the science drivers for, the **V**isible **I**ntegral-field **R**eplicable **U**nit **S**pectrograph (**VIRUS**). This instrument is made up of 145 individually small and simple spectrographs, each fed by a fiber integral field unit. The total VIRUS-145 instrument covers ~30 sq. arcminutes per observation, providing integral field spectroscopy from 340 to 570 nm, simultaneously, of 35,670 spatial elements, each 1 sq. arcsecond on the sky. This corresponds to 15 million resolution elements per exposure. VIRUS-145 will be mounted on the Hobby-Eberly Telescope and fed by a new wide-field corrector with 22 arcminutes diameter field of view. VIRUS represents a new approach to spectrograph design, offering the science multiplex advantage of huge sky coverage for an integral field spectrograph, coupled with the engineering multiplex advantage of >100 spectrographs making up a whole. VIRUS is designed for the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) which will use baryonic acoustic oscillations imprinted on the large-scale distribution of Lyman-α emitting galaxies to provide unique constraints on the expansion history of the universe that can constrain the properties of dark energy.

Keywords: Astronomical instrumentation: Spectrographs, Integral Field, VIRUS, IFU

1. INTRODUCTION

Large targeted surveys of continuum-selected objects are now becoming the norm, and have greatly increased our understanding in many areas of astronomy. Surveys of the emission-line universe, however, are limited currently to wide field imaging with narrow band filters or to narrower fields with Fabry-Perot etalons. Integral field (IF) spectrographs offer a huge gain over these techniques, providing much greater sensitivity, or much greater wavelength coverage, respectively. The current generation of IF spectrographs are well-adapted to arcminute-scale fields of view, with several thousand spatial elements, and adequate spectral coverage for targeted observations of individual extended objects. They have the grasp to detect simultaneously of order 0.5 million (spectral x spatial) resolution elements.

The traditional astronomical instrument has a monolithic design and is a one-off prototype, where a large fraction of the cost is expended on engineering effort. As telescope size increases, geometric considerations are forcing us to the point where the size and cost of spectrographs for the current generation of very large telescopes (VLTs) is approaching a limit. The physical size of VLT instruments (particularly those mounted at Nasmyth foci) is such that careful design and active correction of flexure is needed to maintain instrument alignment. This complexity is reflected in the $20M

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price tags for typical instruments, when engineering costs are fully accounted for. These problems increase for the next generation of extremely large telescopes[1].

Instrumental pupil diameter growth can be mitigated by multiplexing. There are several ways to approach multiplexing, all of which would allow the size of individual spectrographs to be limited: image slicing of a single image or small field of view into a single spectrograph; pupil slicing of a single image into single or multiple spectrographs; and field slicing into multiple spectrographs. When compared to monolithic instruments, there are cost savings from creating several copies of a spectrograph to gain multiplex advantage, because the optics are less expensive and the engineering is simplified. Several current instruments use small-scale replication to achieve multiplex advantage. These include the DEIMOS[2] and VIMOS[3] imaging spectrographs with two and four copies of
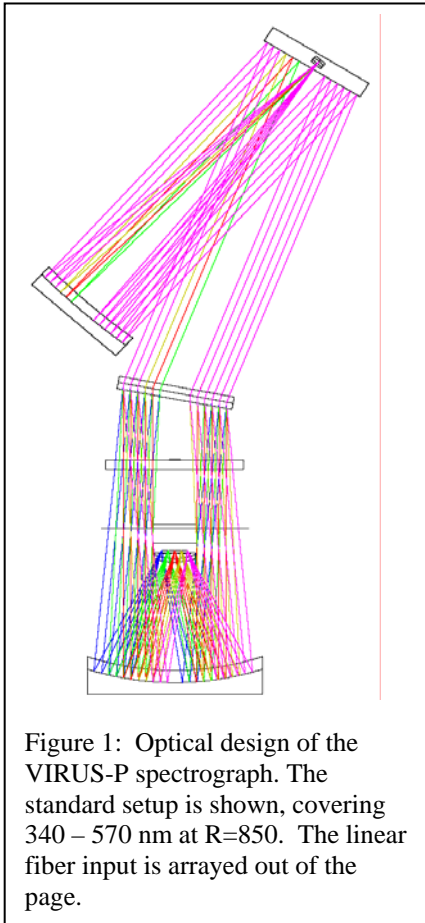
Figure 1: Optical design of the VIRUS-P spectrograph. The standard setup is shown, covering 340 – 570 nm at R=850. The linear fiber input is arrayed out of the page.

Figure 2: Reflective optics of VIRUS-P prior to coating with high reflectivity dielectric mirror coating. For scale, the collimator mirror in the foreground has a width of 300 mm. The flat mirror folds the collimator and has a recess to allow the fiber output pseudo-slit to be arrayed close to the reflective surface of the mirror, minimizing the obstruction of the slot in the mirror. The collimator mirror and camera mirror (rear right) have spherical backs to minimize weight, and were optimized with finite-element analysis to minimize weight. Flats on their rear sides will be bonded to Invar disks for mounting. All substrates are fused silica.

each, respectively, within single structures. The MUSE instrument[4] for ESO VLT will field-slice a 1 arcmin. square field into 24 duplicated spectrographs.

Here we make the next step, and explore the design of an instrument that uses industrial-scale replication, which we (arbitrarily) define to be in excess of 100 units. This paper builds upon the concepts laid out in Hill & MacQueen (2002)[5], and Hill et al (2004)[6], where we concluded that industrial replication offers significant cost-advantages (roughly a factor of two) when compared to a traditional monolithic spectrograph, particularly in the cost of the optics and engineering effort. The aim is to outfit the 9.2 m Hobby-Eberly Telescope (HET[7,8]) with a new wide-field survey capability[9]. HET represents an extreme among current VLTs due to its large pupil size coupled with a site that delivers 1.0 arcsec FWHM median images, exacerbating the instrument pupil-size problem, and making it comparable to a 30 m telescope on a 0.3 arcsec site, from an instrument design point of view. We present the design of the Visible Integral-field Replicable Unit Spectrograph (VIRUS), a simple, modular integral field spectrograph that is replicated 145-fold, to cover what is a very wide field of view for an integral field[6]. The engineering effort is expended in developing a prototype and designing for minimum cost of manufacture, and we expect the engineering costs to be ~1/10 of the total,

rather than >1/2 in the case of a conventional instrument. This savings in engineering effort, coupled with lower unit cost for the optics and simplicity of design, allows a powerful instrument to be realized for a significantly lower investment. This concept breaks new ground and appears to be a cost-effective approach to outfitting the coming generation of ELTs, for certain instrument types.

2. HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT (HETDEX)

There are numerous science projects that can be pursued with a wide-field integral field spectrograph on a large telescope. In the most general sense, such an instrument would open up the emission-line universe to systematic surveys for the first time, uncovering populations of objects selected by their line emission rather than by their continuum emission properties. Here we focus on the main science driver for VIRUS on the HET, mapping the expansion history of the universe in order to constrain the properties of dark energy.

The discovery that the expansion rate of the Universe in recent epochs is dominated by an unknown dark energy[10] is of profound importance. Understanding the nature of Dark Energy (DE) is arguably the most important question facing Astrophysics today, and several experimental techniques are being developed to attack the problem. DE is only observable through its effect on the evolution of the geometry of the universe, so observations that measure the Hubble parameter, luminosity distance, or angular diameter distance can be used to constrain the expansion history of the Universe and hence the equation of state of the DE. Progress on the question of the nature of dark energy requires more information about its properties beyond its mere existence, and major observational projects are planned to trace its effect on the expansion history of the Universe. At redshifts larger than z~1.5 tracers such as supernovae, clusters, and weak lensing become ineffective due to detection issues and crowding. At these redshifts the only suitable tracer of the expansion history is the imprint of the baryonic acoustical oscillations, seen in the CMB[11], on the large-scale distribution of galaxies[12]. Very large surveys are required to achieve statistics sufficient to provide constraints on DE by this method, but the power of this approach lies in its insensitivity to systematics, and in its simple geometric application. Comparison of the angular scale size of the peaks of the oscillations with the scale size in the redshift dimension provides direct measurement of the angular diameter distance to, and the Hubble parameter (expansion rate) at, that redshift[13]. The angular diameter distance to the redshift in question and the Hubble parameter integrate over the geometry of the universe back to that redshift, including the effects of any time variability of the equation of state of the DE. A large redshift survey over $2 < z < 4$ provides unique and powerful constraints on the evolution of DE[14].

As a driver for the VIRUS spectrograph we consider the large-volume survey of large-scale structure (LSS) required to detect the relic of the baryonic acoustical peaks at $2 < z < 4$ and constrain the equation of state of the dark energy to better than 10%. In combination with the surveys targeting lower redshifts, this survey – the Hobby-Eberly Telescope Dark Energy Experiment – will allow us to trace the expansion history of the Universe from the present epoch back to z~4. In order to realize a survey of LSS at high redshift covering sufficient volume a highly multiplexed spectrograph is required. The basic requirement for sufficient statistics is to survey a volume ~5 Gpc^3 containing ~1 M galaxies[13,14]. This translates to an area ~250 sq. degrees with Δz~2 at z~3.

The optimum design of the instrument depends on the tracer. Lyman-break galaxies (LBGs) have been suggested as tracers of LSS at z~3 (refs 13). They are easily found in deep imaging surveys and could be targeted by a multi-fiber spectrograph with very wide field of view (2 sq. degrees or larger) on an 8 m class telescope. The relatively low surface density of LBGs, ~1 per sq. arcminute, is well suited to a multi-fiber system where crowding is an issue.

Lyman-α emitting galaxies (LAEs) are an alternative tracer of LSS[14]. They have much higher space density, and have the advantage that obtaining redshifts from emission lines requires significantly less integration time. LAEs have a surface density ~20,000 per sq. degree at a line flux limit of ~2e-17 erg/cm^2/s, a level reached in a short (1200 s) obsevations with an integral field spectrograph with resolving power R~1000 on an 8 m class telescope. Since the optimal number of tracers is ~2000-3000 per square degree, the required sampling (fill-factor) is ~1/9. If the spatial scale of this sampling is significantly smaller than the projected non-linear scale size, the incomplete fill-factor will have no effect on the power-spectrum. At z~2, this scale size is ~10 arcminutes.

HETDEX[14] will map the spatial distribution of about a million LAEs with redshifts $1.8 < z < 3.7$ over 250 sq. deg. area (5 Gpc^3). This dataset will constrain the expansion history of the Universe to 1% and provide significant constraints on the evolution of dark energy. The integral field spectrograph capable of completing this survey is a very ambitious instrument, but it can be realized with the VIRUS module and industrial replication. With these requirements in mind we turn to the detailed design of the instrument.

3. DESIGN OF THE VIRUS PROTOTYPE

The VIRUS module consists of a fiber-coupled IFU feeding a single, simple spectrograph. The design and construction of each VIRUS module is well within the state of the art, and industrial replication is used to build many copies of the module to be integrated into a single instrument. We have undertaken a detailed design study of the VIRUS unit spectrograph resulting in the construction of a prototype (VIRUS-P) that tests many of the features of the final instrument.

3.1 Optical Design

In the course of developing the prototype of the VIRUS module, we first investigated refractive optical designs with beam sizes between 75 and 100 mm. The field angles required to accept the number of fibers, coupled with the desire for coverage into the ultraviolet, proved difficult for designs without large numbers of elements and use of calcium fluoride. Evaluation of the throughput, the weight, and the cost of these designs led us to investigate catadioptric alternatives, where we knew we could obtain high throughput at relatively low cost. Comparison of real designs showed that when glass absorption and anti-reflection coatings were taken into account, the refractive designs did not have a significant throughput advantage over those with mirrors. This approach was not our first line of investigation mainly because it necessitates a cryogenic camera with the detector at an internal focus, but such designs are pan-chromatic and can be very efficient, as demonstrated by the camera for the HET Low Resolution Spectrograph, for example[15]. This is particularly true of designs with limited bandwidth where very high reflectivity coatings can be applied. Table 1 summarizes the designs evaluated.

The final design is shown in Figure 1. The input focal ratio is f/3.65 and the camera focal ratio is f/1.33. Details of the design will be given elsewhere. It consists of a reverse-Schmidt collimator, where the input fibers are arrayed pointing perpendicular to the spherical collimator mirror so as to create an axis-less system. A cylindrical lens is coupled to the fibers to provide immersion of the ends and an AR coated exit face for maximum efficiency. A fold mirror is introduced for compactness and to allow flexibility in the design of the integral field unit interface. The disperser is a volume phase holographic grating with 831 fringes/mm sandwiched between fused silica plates. The camera is a Schmidt with aspheric corrector plate and an aspheric surface on the back side of the field flattener lens, both of fused silica. It was found that the correction for both the collimator and camera could be achieved with a single asphere on the camera corrector, which also acts as the window for the vacuum housing of the camera. This design achieves superb images, far superior to those achieved with the refractive designs we investigated. Modeling of data frames has included the convolved image quality and distortion predicted from the optical design and shows well-separated spectra from the individual fibers. This is important in reducing cross-talk and enabling straight-forward extraction of the individual spectra

Table 1: VIRUS optical designs evaluated

Type	Beamsize	Camera f/ratio	# camera elements	Element weight	RMS image quality	Comment
refractive	75 mm	f/1.9	7	7.5 kg	50 μm	wavelengths 340-505 nm
refractive	100 mm	f/1.4	9	13.5 kg	60 μm	CaF_2, wavelengths 340-570 nm
catadioptric	110 mm	f/1.369	4	8 kg	10 μm	doublet corrector, 340-570 nm
catadioptric	115 mm	f/1.33	3	5.85	6 μm	Adopted design, 340 -570 nm

The VIRUS-P optics are complete, coated, and awaiting integration into the instrument at the time of writing. The mirrors were manufactured by Harold Johnson Optical Labs, and were designed with spherical rear surfaces to minimize weight. Figure 2 shows the mirrors prior to coating. They were coated with a high efficiency dielectric mirror coating by ZC&R achieving an average >98.5% reflectivity over 340-670 nm with no dips below 95%. The aspheric elements were manufactured by Asphericon using CNC grinding/polishing, which easily met the specifications on figure. The design works far from the diffraction limit, so few-wave errors are acceptable and now within the capabilities of mass-production.

Table 2: basic properties of VIRUS

IFU	246 fibers, each 200 μm diameter or 1.0 sq. arcsec. area. Square format 29 x 29 arcsec^2, 1/3 fill-factor, hexagonal pack fed at f/3.65 at prime focus of HET
	On the McDonald 2.7 m Smith reflector, fibers are 4.16 arcsec. diameter, 13.6 sq. arcsec. area
Collimator	accepts f/3.35, folded reverse-Schmidt reflective design, without corrector
Camera	f/1.33 Schmidt with 2k x 2k 15 μm pxl CCD at internal focus. Aspheric corrector plate and field flattener. Fiber reimaged to 4.9 pixels
Disperser	831 l/mm VPH grating gives 340-570 nm simultaneous coverage at R~850; dispersion 0.11 nm/pixel 0.56 nm per resolution element
VIRUS-145	35,670 fibers; 9.9 sq. arcmin. per exposure; 30 sq. arcmin per observation of 3 dithered exposures; 15 million resolution elements per exposure; 1.4 Gb per exposure

    The standard setup for HETDEX employs a volume phase holographic (VPH) grating with 831 fringes per mm, and Bragg angle close to 11 degrees. The clear aperture of the grating is 130 mm. We have developed a series of replicated gratings in collaboration with Wasatch Photonics, with the aim of reducing the unit cost and maximizing the uniformity of properties of a large order of gratings. Initial tests of the replicated gratings show that this approach is promising, and we will evaluate full-size gratings made be conventional exposure and by replication in the VIRUS prototype.

    The catadioptric design of VIRUS allows other modes with higher resolving powers and different wavelength coverage[6]. One of the aims of VIRUS-P is to test such modes, and the instrument can cover wavelengths as red as 670 nm and provide resolving powers as high as R=4000, by substituting the grating for one with higher dispersion and setting the collimator and grating angles appropriately. Angles of incidence as high as 45 degrees onto the grating are allowed by the mechanical design. While these options open up interesting observing projects, an evaluation of the science drivers for a fully reconfigurable VIRUS-145 has led us to adopt a standard fixed low resolution format for the instrument rather than incur the complexity and cost of allowing all units to be reconfigured. Among the final array of VIRUS units we will include several that are configurable to allow higher resolving power observations of small fields of view.
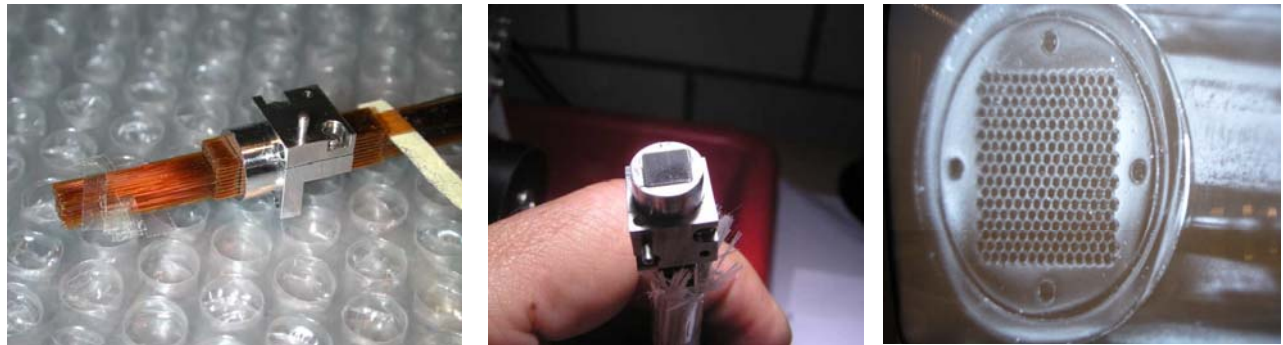

Figure 3: Fiber IFU development. The left panel shows the assembly of the AIP fiber head with a matrix of fused silica capillary tubes clamped in a stainless steel fixture and then filled with fibers. The middle panel shows the same bundle after gluing with Epotek 301-2 low-shrinkage epoxy, cutting and polishing. The head has very small size allowing IFUs to be spaced with a fill-factor as tight as ¼. The right hand panel shows the head of the bundle produced by Fibertech, where the fibers were set into drilled stainless steel plates, bonded and polished.

3.2 Integral Field Units

The HET tracker carries the spherical aberration corrector, positioning it with a hexapod system. This hexapod would be unable to support the weight of a large prime-focus spectrograph utilizing coherent image slicers, so fiber-coupled IFUs are required. Fiber IFUs can utilize microlens arrays, providing close to 100% fill-factor[16], or be of the simpler "densepak" type[17]. For VIRUS we have elected to use the densepak type of bare fiber bundle to maximize throughput and minimize cost[18]. The primary advantage of lenslets is in coupling the slower f/ratios of typical foci to the fast ratio required to minimize focal ratio degradation[19], and such IFUs are ideal for retro-fitting existing spectrographs. Lenslets do not provide perfect images, however, so if there is flexibility to choose the input f/ratio to the fibers and if the fill-factor can be tolerated, trading it against total area, the bare bundle provides the best efficiency[6,20]. We use a fill factor of 1/3, with the fibers in a hexagonal close pack, and dither the IFU arrays through three positions to fill the area. Note that if the f/ratio of the microlens case is the same as the f/ratio from the telescope in the bare-fiber case, and the lenslets subtend the same area on the sky as the bare fibers, then the fill-factor of the densepak type array is exactly offset by the larger area that the bundle covers per exposure. So in the case where maximum areal coverage is required, the bare bundle is the preferred solution[20].

The HET site has a median seeing of 1.0 arcsec. FWHM, and we adopt 1 sq. arcsec. per fiber as an optimal compromise between sensitivity and area coverage. The base IFU has 246 fibers in a hexagonal packing pattern with a 1/3 fill factor (Table 2). The current HET corrector is f/4.65, but the future wide-field corrector will have f/3.65. At this f-ratio a 200 μm core fiber has the desired 1 sq. arcsec. area. The optics of VIRUS can accommodate an f/ratio of f/3.35, allowing a degree of focal ratio degradation. Detailed testing of fibers from Polymicro (FB200220240) and FiberTech (AS200220UVPI) shows that this f-ratio accepts over 95% of the light input at f/3.65[20,21].
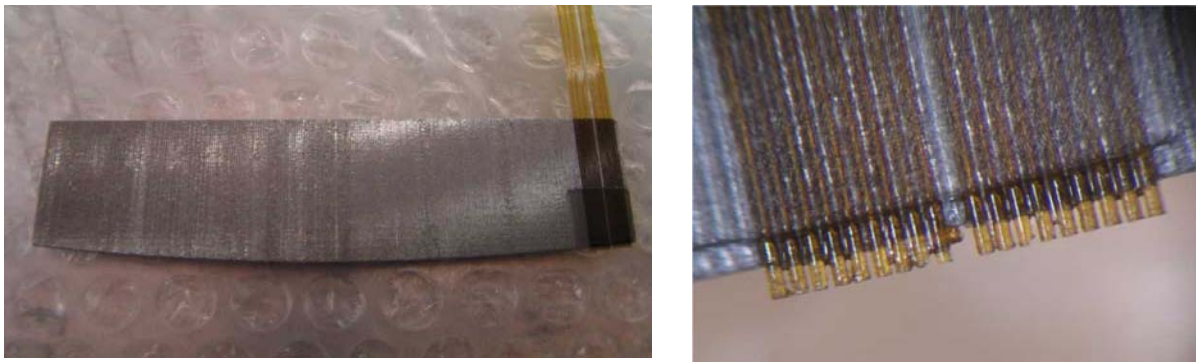

Figure 4: The pseudo-slit output of the IFU bundles. The fibers are arrayed on a precision grooved plate that sets the spacing and angle between fibers. The fibers are arrayed perpendicular to the back surface of a cylindrical lens bonded to the convex surface of the plate. The right panel shows a close-up of a test binding of fibers, which demonstrated high precision in placing the pre-polished fibers in position. The pitch of the fibers is 320 μm, resulting in a separation of 7.8 pixels on the CCD.

Development of the prototype IFU at AIP[20] has explored several ways of setting up the required matrix of fibers at the input end. Drilled plastic aperture plates can achieve the desired spacing accuracy but present problems for polishing as the plastic smears [20,21]. Setting up a matrix fused silica capillary tubes to set the spacing proved very successful. The fibers are easily threaded into tubes with only 5 μm clearance on the diameter, and these arrays were measured to have final fiber position errors of less than 5 μm rms. This is well within the requirements. One fiber bundle has been assembled with Polymicro FBP fibers, using this method at AIP. Another fiber bundle has been produced by FiberTech using drilled aperture plates of stainless steel. Figure 3 shows the input ends of the two bundles. Anti-reflection coated fused silica cover plates will be bonded to the polished surface of each IFU to minimize insertion losses.

At the output of the bundle, the fibers are arrayed in a line, immersed against the curved back face of a cylindrical lens, and fanned out with their axes pointing perpendicular to the collimator mirror (and to the lens). The spacing of 320 μm with 0.043 degrees between fibers. This layout allows collimation of the beam to be achieved with only one spherical mirror, leading to a very efficient design. The layout is achieved by bonding the fibers to a monolithic groove plate of stainless steel. Figure 4 shows the plate with test fibers bonded in place. The first of the bundles will be completed at the end of June.

3.3 Mechanical Design

The VIRUS prototype is being developed for use as a test bed for the design and will be used for an extensive survey of Ly-α emitting galaxies on the McDonald 2.7 m Smith Reflector. As a result, we required it to operate with high stability under a wide range of temperature from -5 to +25 degrees Celsius. We require that the instrument not require recalibrating for the positions of the fiber images over the full temperature range. This corresponds to shifts smaller than 0.5 pixels (1/10 of a resolution element) at the detector. Stability of image quality throughout the range of angles of the collimator and grating is required, but repeatability of setup is only at the resolution element level. The final design for VIRUS on HET (see below) may not require such a constraint if the units are housed in an environmentally controlled housing, but we decided to impose the strictest requirements on the prototype in order to prove engineering concepts that might be required for the final instrument. In addition, we designed the prototype to test all possible modes of the instrument, including a range of resolving powers and wavelengths, even if these will not be options for the majority of VIRUS units, in practice.

Figure 5: Mechanical design of VIRUS-P
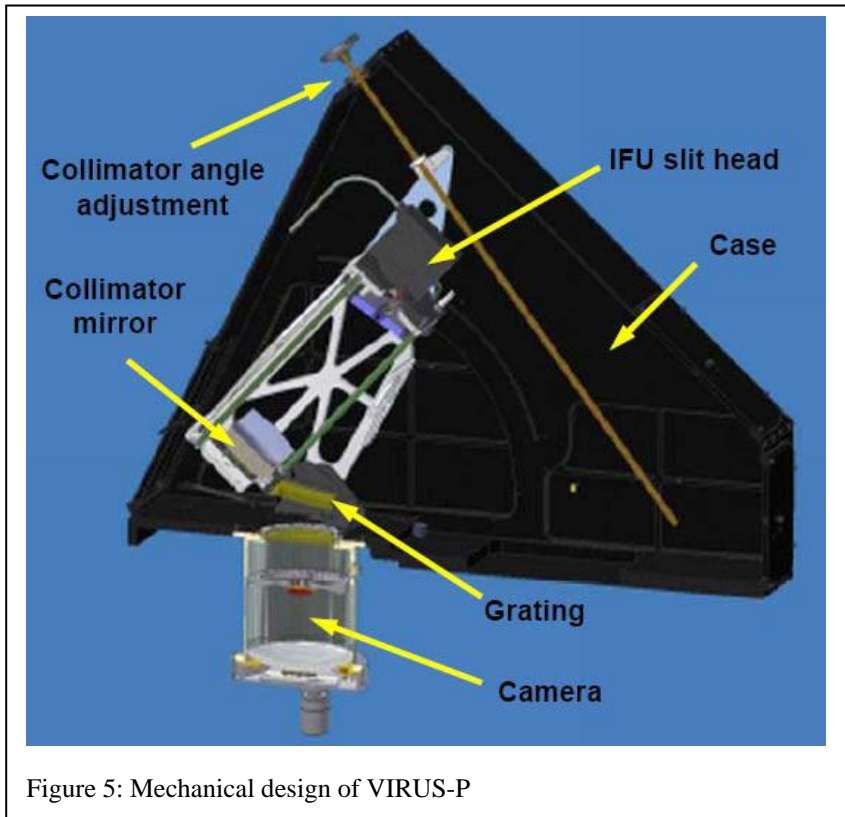
The mechanical design is shown in Figure 5. The instrument has a collimator and disperser module and a camera with a cryogenic detector head at its internal focus. The majority of the collimator parts are of Aluminum with Invar metering rods maintaining the spacing between the collimator mirror and the IFU output. Three invar rods act as rails to which the optics are mounted, with simple adjustments and clamps. The rods are bolted at one end to the IFU reference plate of Aluminum (to which the IFU slit head mounts), and at the other to disk flexures mounted in an Al plate. This setup effectively allows the structure to have the CTE of Al in all dimensions except the optical axis where invar is needed to maintain focus.

The camera is designed to have the highest stability by adopting Invar for the cryostat housing and all internal pieces. The goal is to able to set up the alignment at room temperature and not have to adjust it again. The tolerance on the focus change for example is smaller than 20 microns over the full temperature range. The detector and field flattener are suspended in the beam with an Invar spider assembly that also carries the cold link and flex circuit. The design has been optimized for minimum obstruction

3.4 Camera and Detector System

The camera has f/1.33 for the nominal pupil size of 115 mm, and accepts light from a 125 mm diameter pupil with little vignetting. The optics consist of the fused silica window which has an aspheric front surface (maximum deviation 0.3 mm), the spherical mirror, and the fused silica field flattener with a spherical front and aspheric back surface. The detector and field flattener are suspended in the beam, causing approximately 23% obstruction, on axis (in the absence of FRD which spreads the light over a larger effective pupil diameter and reduces obstruction). Otherwise the design has very high efficiency, and produces superb images. High quality images are required so as to maintain sufficient separation between the spectra from individual fibers on the detector, to allow clean extraction of the spectra. The CCD will be a 2k x 2k x 15 μm pixel CCD. Yields on this relatively small format detector are very high and they represent the lowest cost per pixel for science-grade devices. Working into the near-UV, low readout noise and good UV-blue QE are important considerations. Available detectors from Fairchild and E2V can meet the needs of the instrument.

The prototype uses an existing older CCD from Orbit. It has higher readout noise (around 6 electrons at 100 kpxl/s) than chips being considered for the final design of VIRUS, but this is of less concern as the instrument will be primarily used on the 2.7 m telescope where the fibers subtend 13 sq. arcsec. on the sky (Table 2), and exposure times will be long enough to be background-limited.

The fiber resolution element is reimaged to 4.9 pixels. At 7.8 pixel spacing between fibers, the 246 fibers of the IFU can be accommodated on the detector. The detector can record 430 spectral resolution elements for each fiber, so each spectrograph surveys 105k spectral*spatial resolution elements per exposure. This uses the available CCD real estate with 60% efficiency (fill-factor). The full VIRUS-145 records 15 million resolution elements simultaneously. This is larger than any spectrograph in current use.

A system with 145 CCDs requires a highly parallelized readout in order to avoid unacceptable overheads. The VIRUS configuration lends itself to a modularized controller design. We intend to reconfigure the McDonald Observatory Version 2 CCD controller, simplifying it to a single mode, and laying out boards to simplify assembly, including machine assembly of many components. At 200 kpxl/sec readout rate, this controller should provide a read-noise of 2.7 electrons or less with available detectors, and a read-time of ~20 seconds per channel.

3.5 Cost

Table 3 Cost estimate for VIRUS replication including contingency

Item	replication cost $k	total cost $M
IFU	14.7	2.65
Optics and mechanics	34.4	5.45
Detector/cryostat	36.6	6.08
Tooling, spares, enclosure	--	0.86
Totals	85.7	15.04

A key aspect of the design development for the VIRUS prototype has been the evaluation of the cost of replicating the design. The mechanical design of the prototype is more complex than the final replicated unit will be, and uses an existing CCD and controller. It has been constructed for $108k and 5.5 person years of effort. Much of the engineering will be applicable in concept if not in detail to the final replicated unit, which we estimate can be constructed for $86k in quantity, based on direct experience with the prototype and quotations for parts in volume. The breakdown of the cost for the replicated instrument is given in Table 3. We estimate these costs apply to minimum batches of 50 units.

4. VIRUS-145 ON THE HOBBY-EBERLY TELESCOPE

The HET is a revolutionary telescope with an 11 m hexagonal-shaped spherical mirror made of 91 1 m hexagonal segments that sits at a fixed zenith angle of 35°. It can be moved in azimuth to access about 70% of the sky visible at McDonald Observatory[†]. The pupil is 9.2 m in diameter, and sweeps over the primary as the x-y tracker follows objects. A 4-mirror Gregorian-type corrector delivers a 4-arcminute diameter science field of view. The HET site delivers 1.0 arcsec FWHM median seeing. The relatively small field of view of the current corrector is uncompetitive, and we plan to outfit the telescope with a new wide field (20 arcmin. diameter) corrector and instrument payload on a timeframe of 3-5 years. Details of the performance of HET and the upgrade can be found in refs 7-9.

The VIRUS spectrograph is well-suited to HET. The fiber IFU feed allows the weight of the instrument to be off-loaded from the hexapod system, which has limited capacity, and the fibers azimuthally scramble the far-field image of the varying pupil illumination, allowing higher precision in calibrations by removing the majority of the time-variability. The limited track-times available with HET make rapid acquisition and setup essential, since setup time directly reduces integration time, and VIRUS requires no setup beyond pointing. There are several possible locations for mounting VIRUS on HET: on the carriage that moves on the tracker beam, on the ends of the tracker beam itself, or at various positions around the top structure of the telescope. Fiber length increases between these options, but complexity decreases.

Following an extensive evaluation of mounting options and their result on fiber length, the two options are illustrated in Figure 6. The left panel shows the spectrographs arrayed in banks within the central obstruction of the corrector. This case allows a minimal fiber length of about 4 m. This location is subject to strict weight and space limits, but offers the best UV performance by minimizing fiber losses. The alternative location would array the units in two environmentally controlled enclosures mounted on the top hexagonal structure of the telescope, as shown in the right panel of Figure 6. The fiber length for this option is 14 m.. At 14 m length, the throughput at 340 nm drops by 2% in absolute terms, which is acceptable (see Section 5), given the probable cost savings allowed by relaxing the weight limit.

5 PREDICTED PERFORMANCE

The design of the individual VIRUS spectrograph modules lies well within the state of the art, and estimation of performance is relatively straight-forward. The largest uncertainty lies in the throughout of the fiber IFU, mainly in accounting for insertion losses and focal ratio degradation (FRD). Detailed testing of the fibers[18,20] at AIP indicates that for the fast f/ratio considered here the FRD is minimal so long as care is taken in the assembly of the bundles so as to avoid stresses in the fibers. With optimized coatings, the optics, VPHG disperser, and CCD can detect 25% to 40% of the photons over the bandpass, while the atmosphere and telescope have 30-50% throughput. These estimates combine to give the efficiencies between 5% at 340 nm and 18% at 450 nm. The resulting sensitivity for the target line flux is $\sim 1 \times 10^{-17}$ erg/cm^2/s for the baseline 20 minute observation. It is evident that VIRUS has adequate sensitivity to reach the goals of HETDEX, and will obtain useful spectra of all objects with AB<23.5 in the observed field of view. Throughput of the prototype on the McDonald 2.7 m is somewhat lower, peaking at 15%, but is similar at 340 nm.

With this sensitivity, and with efficient target setup, it will be possible to observe a total of ~0.3 sq. degrees per night distributed within a total area of 2.5 sq. degrees. For HETDEX, sparse sampling of the volume is acceptable, so 250 sq. degrees can be surveyed with $\Delta z\sim2$ in ~110 nights. This corresponds to a volume of 5 Gpc^3, in a survey that would occupy the HET for the dark time of three spring trimesters.

[†] HET is a collaboration of the University of Texas at Austin, Pennsylvania State University, Stanford University, Georg-August-Universität, Göttingen, and Ludwig-Maximillians-Universität, Munich.
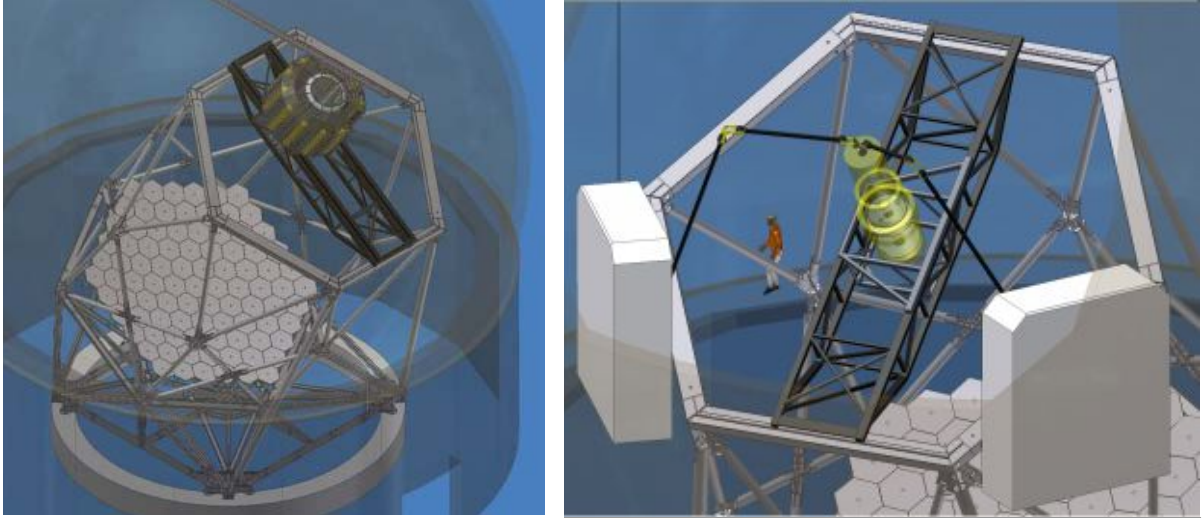
Figure 6: Conceptions of VIRUS-145 on the HET tracker beam. In the left panel, the spectrographs are arrayed in modules around the prime focus of the telescope, within the central obstruction of the new wide field corrector. The load is carried by the tracker carriage or on a separate slaved tracker. In the right panel, the spectrographs are arrayed in two environmentally controlled enclosures mounted to the HET structure. The fiber length for the integral field units for this configuration is 14 m, routed through articulated "spider legs" as shown to follow the motion of the tracker. We have investigated a wide range of locations for the instrument, from within the central obstruction of the corrector to various positions on the tracker beam and telescope structure. Among the off-tracker options the one shown provides the best location for fiber length and wind-sail area.

6. SUMMARY

Development of the VIRUS instrument is proceeding along with fundraising for HETDEX. The prototype of VIRUS will be completed this summer and used for a 50 night survey of the properties of Lyman-α emitting galaxies. About half the funding for HETDEX is in hand or committed, sufficient to complete the wide field upgrade of the HET and to complete the design of the final VIRUS unit for replication. With funding, the modifications to HET and the replication of 145 VIRUS units can be completed in 2010 and the HETDEX survey in 2012. When completed, the combination of HET and VIRUS will provide an unequalled survey facility with a grasp over an order of magnitude larger than any current instrument.

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REFERENCES

1. A.P. Russell, G. Monnet, A. Quirrenbach, R. Bacon, M. Redfern, & T.G. Hawarden, "Instruments for a European ELT: The callenges of designing instruments for 30- to 100-m telescopes", Proc. SPIE, **5492**, 1796, 2004
2. S. Faber *et al*., "The DEIMOS spectrograph for the Keck II Telescope: integration and testing," Proc. SPIE, **4841**, 1657, 2003
3. O. Le Fevre *et al*., "VIMOS and NIRMOS multi-object spectrographs for the ESO VLT," Proc. SPIE, **4008**, 546, 2000
4. R.M. Bacon "Probing unexplored territories with MUSE: a second generation instrument for VLT", *Proc. SPIE*, **6269**, paper 6269-19, 2006
5. G.J. Hill, & P.J. MacQueen, "VIRUS: an ultra cheap 1000-object IFU spectrograph", Proc. SPIE, **4836**, 306, 2002
6. G.J. Hill, P.J. MacQueen, C. Tejada, P.J. Cobos, P. Palunas, K. Gebhardt, & N. Drory, "VIRUS: a massively-replicated IFU spectrograph for HET," *Proc. SPIE*, **5492**, 25, 2004
7. G.J. Hill, P.J. MacQueen, L.W. Ramsey, & M.D. Shetrone, " Performance of the Hobby-Eberly Telescope and Facility Instruments**"**, Proc. SPIE, **5492**, 94, 2004
8. G.J. Hill, P.J. MacQueen, M.D. Shetrone, & J.A. Booth, "Present and future instrumentation for the Hobby-Eberly Telescope", *Proc. SPIE*, **6269**, paper 6269-5, 2006
9. J.A. Booth, P.J. MacQueen, J.G. Good, G.L. Wesley, P.R. Segura, P. Palunas, G.J. Hill, R.E. Calder, "The Wide Field Upgrade for the Hobby-Eberly Telescope", Proc. SPIE, **6267**, paper 6267-97, 2006
10. A.G.Riess *et al*., "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant," AJ, **116**, 1009, 1998
11. D.N. Spergel, *et a*l., "First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Interpretation of the TT and TE Angular Power Spectrum Peaks ," ApJS, **148**, 175, 2003
12. D. Eisenstein et al., "Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies", ApJ, **633**, 560, 2005
13. C.A. Blake & K. Glazegrook, "Probing Dark Energy Using Baryonic Oscillations in the Galaxy Power Spectrum as a Cosmological Ruler ," ApJ, **594**, 665, 2003; H.-J. Seo & D.J. Eisenstein, "Probing Dark Energy with Baryonic Acoustic Oscillations from Future Large Galaxy Redshift Surveys ," ApJ, **598**, 720, 2003
14. G.J. Hill, K. Gebhardt, E. Komatsu, & P.J. MacQueen, "The Hobby-Eberly Telescope Dark Energy Experiment", in *The Mitchell Symposium on Observational Cosmology*, *AIP Conf. Proc*., **743**, 224, 2004
15. Hill, G. J., Nicklas, H., MacQueen, P. J., Tejada de V., C., Cobos D., F. J., and Mitsch, W., "The Hobby-Eberly Telescope Low Resolution Spectrograph", in *Optical Astronomical Instrumentation*, S. D'Odorico, Ed., Proc. SPIE **3355**, 375, 1998.
16. e.g. J.R. Allington-Smith *et. al*., "Integral Field Spectroscopy with the Gemini Multiobject Spectrograph. I. Design, Construction, and Testing", PASP, **114**, 892, 2002
17. S.C. Barden & M.A. Wade, "DensePak and spectral imaging with fiber optics", in *Fiber optics in astronomy*; Proceedings of the Conference, Tucson, AZ, Apr. 11-14, 1988 (A90-20901 07-35). San Francisco, CA, Astronomical Society of the Pacific, 1988, p. 113-124
18. A. Kelz, S.M. Bauer, F. Grupp, G.J. Hill, E. Popow, P. Palunas, M.M. Roth, P.J. MacQueen, & U. Tripphahn, "Prototype development for the integral-field unit for VIRUS", Proc. SPIE, **6273**, paper 6273-151, 2006
19. e.g. J. Schmoll, M.M. Roth, & U. Laux, "Statistical Test of Optical Fibers for Use in PMAS, the Potsdam Multi-Aperture Spectrophotometer," PASP, **115**, 854, 2003
20. A. Kelz, M. Verheijen, m.m. Roth, & U. Laux, "Development of the wide-field-IFU PPAK," Proc. SPIE, **5492**, paper 187, 2004
21. G.J. Hill, P.J. MacQueen, P. Palunas, A. Kelz, M.M. Roth, K. Gebhardt, & F. Grupp, "VIRUS: a hugely replicated integral field spectrograph for HETDEX", *New Astronomy Reviews*, in press, 2006