

Astro2020 APC White Paper

FOBOS: A Next-Generation Spectroscopic Facility

Thematic Areas: Project Paper

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Abstract:

High-multiplex and deep spectroscopic follow-up of upcoming panoramic deep-imaging surveys like LSST, Euclid, and WFIRST is a widely recognized and increasingly urgent necessity. No current or planned facility at a U.S. observatory meets the sensitivity, multiplex, and rapid-response time needed to exploit these future datasets. FOBOS¹, the Fiber-Optic Broadband Optical Spectrograph, is a near-term fiber-based facility that addresses these spectroscopic needs by optimizing depth over area and exploiting the aperture advantage of the existing 10m Keck II Telescope. The result is an instrument with a uniquely blue-sensitive wavelength range (0.31–1.0 μm) at $R \sim 3500$, high-multiplex (1800 fibers), and a factor 1.7 greater survey speed and order-of-magnitude greater sampling density than Subaru’s Prime Focus Spectrograph (PFS). In the era of panoramic deep imaging, FOBOS will excel at building the deep, spectroscopic reference data sets needed to interpret vast imaging data. At the same time, its flexible focal plane, including a mode with 25 deployable integral-field units (IFUs) across a 20 arcmin diameter field, enables an expansive range of scientific investigations. Its key programmatic areas include (1) nested stellar-parameter training sets that enable studies of the Milky Way and M31 halo sub-structure, as well as local group dwarf galaxies, (2) a comprehensive picture of galaxy formation thanks to detailed mapping of the baryonic environment at $z \sim 2$ and statistical linking of evolving populations to the present day, and (3) dramatic enhancements in cosmological constraints via precise photometric redshifts and determined redshift distributions. In combination with Keck I instrumentation, FOBOS also provides instant access to medium-resolution spectroscopy for transient sources with full coverage from the UV to the K-band.

¹fobos.ucolick.org

1. SCIENTIFIC MOTIVATION

1.1. Community Need. The need for spectroscopic follow-up in the LSST era was made clear in the National Research Council’s 2015 report, “Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System” (Council, 2015):

The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way.

Workshops organized by the National Optical Astronomy Observatory (NOAO) in 2013 and 2016 reported specific spectroscopic needs for LSST follow-up in all science areas. In particular, the 2016 report notes that a critical resource in need of prompt development is to “Develop or obtain access to a highly multiplexed, wide-field optical multi-object spectroscopic capability on an 8m-class telescope.” More recently, the need for significant investment in spectroscopic facilities was highlighted in multiple Astro2020 Science White Papers, many of which we refer to when motivating our science cases below.

FOBOS takes a critical first step in addressing these needs using an existing telescope to achieve a final cost ≈ 20 times less than wide-area spectroscopic telescopes of the future, such as the Mauna Kea Spectroscopic Explorer (MSE, Hill et al., 2018) and SpecTel (see Astro2020 APC White Paper). Compared to the Prime Focus Spectrograph (PFS) on Japan’s Subaru Telescope, FOBOS would be $1.7\times$ faster, provide unique UV sensitivity ($0.31\text{--}1\ \mu\text{m}$ compared to $0.38\text{--}1.25\ \mu\text{m}$ with PFS), and offer higher-density, more flexible target sampling over “deep-drilling” fields. Unlike PFS, FOBOS would be operated on a U.S. telescope with dedicated U.S. access and a commitment to supporting U.S.-led imaging facilities.

1.2. Key Science Goals. With its high multiplex and Keck’s large aperture, FOBOS will enable significant progress in multiple science areas by providing much-needed large and deep spectroscopic samples. These unprecedented data sets will be scientific gold mines for the U.S. community in their own right, but when combined with novel observations from forthcoming facilities, transformational advances are possible. These include 1) charting the assembly history of the Milky Way, M31, and Local Group dwarf galaxies by combining deep FOBOS spectroscopy with wide spectroscopic campaigns (e.g., DESI Bright-Time Survey and SDSS-V Milky Way Mapper), GAIA data, and panoramic imaging from LSST, Euclid, and WFIRST; 2) mapping the baryonic ecosystem at $z \sim 2\text{--}3$ and linking it to evolving populations at lower redshifts by training photometric diagnostics that transfer detailed spectroscopic knowledge to billion-plus galaxy samples provided by future all sky surveys; 3) dramatically enhancing cosmological probes using panoramic deep imaging and cross-correlation techniques with Stage-IV CMB observations thanks to precise calibration of photometric redshifts and redshift distributions.

FOBOS addresses these goals by achieving high multiplex while optimizing for sensitivity over area. Future imaging data will routinely reach $i_{\text{AB}} = 25$, yielding target densities of $42\ \text{arcmin}^{-2}$. FOBOS achieves a single-pass on-sky sampling density of $6\ \text{arcmin}^{-2}$ on average, and close packing would allow a maximum target density of $\sim 30\ \text{arcmin}^{-2}$. These capabilities allow FOBOS to collect large samples of very faint sources with highly efficient observing strategies.

Meanwhile, innovations in astrostatistics and machine learning in particular promise powerful synergies between these information-rich but volume-limited FOBOS samples and the vast cosmic volumes that will be surveyed by LSST, Euclid, and WFIRST. As we discuss below, these synergies underlie all three of FOBOS’s broad science goals. Progress in all areas can be carried out with observations that simultaneously integrate multiple programs and observing modes, including a priority on time-domain astronomy. A rapid response capability for high-value transient sources is provided by FOBOS’s fixed, oversized IFU. With FOBOS on Keck II and existing Keck I instrumentation, Keck will enable instant follow-up spectroscopy at medium resolution with full wavelength coverage from the UV to the K-band.

Given the community-wide value of these capabilities and following past examples at Keck (e.g., DEEP2 Newman et al., 2013), FOBOS will play a leading role in obtaining and publicly delivering critical, enabling data sets that leverage major project investments by the U.S. community. These data sets will include raw observations, fully-reduced, calibrated, and processed spectra, and high-level derived data products, including redshifts, measurements of spectral features, and inferred physical information (e.g., stellar parameters, galaxy star formation histories, environmental catalogs). In addition to the 20% of Keck observing time already open to the public, additional FOBOS access may be possible through key programs allocated a specific fraction of FOBOS fiber-hours and combined with other programs into multi-cycle observing campaigns. The FOBOS team will engage in a broad campaign of community engagement in the next year to further define science goals and community access models. We encourage interested parties to contact the first author.

1.3. Assembly History of the Local Group. Studies of individual stars in the Milky Way (MW), Magellanic Clouds, Andromeda (M31), Triangulum galaxy (M33), and numerous dwarf satellites provide an exquisitely detailed look at specific examples of galaxy assembly and evolution. While Gaia provides on-sky motions and photometry for 1.7 billion stars in the MW, fewer than 10%, 0.3%, and 0.1% of stars will have a full complement of astrometrics and kinematics, basic stellar parameters, and chemical abundances, respectively. Moreover, Gaia distance errors increase quadratically with distance. Spectroscopy with APOGEE, the Milky Way Mapper, and WEAVE provide supporting wide-field data sets but accounting for fainter stars requires FOBOS-like sensitivity (see Dey et al., 2019; Sanderson et al., 2019). By carefully exploiting the overlap in these data sets, FOBOS can link high-resolution and robust stellar information from brighter targets to stars that can only be characterized by photometry. This would enable data-driven models capable of providing photometric estimates of stellar parameters (temperature, surface gravity, metallicity, and alpha-element abundance) for *all* stars in the Gaia dataset (see Ness et al., 2015; Ting et al., 2018; Ting & Rix, 2018).

Of particular interest is the ability of future imaging surveys to increase the census of stellar streams and other substructure by a hundredfold. The stars in these structures are faint, however, and easily confused with background galaxies in ground-based photometry. With spectroscopic reference samples from FOBOS, the goal is to photometrically reconstruct the star-formation histories of disrupted satellites and compare them with dynamical models to constrain assembly histories and enclosed mass constraints (e.g., Sanderson et al., 2017).

Performing a similar analysis on the M31 halo is highly desirable but more challenging because individual main-sequence stars at the distance of M31 are too faint for 10m telescopes. Thus spectroscopic training efforts must focus on giant stars in the M31 halo and be calibrated with hydrodynamical simulations that account for M31’s differing formation history (e.g. Renda et al., 2005; Li et al., 2019).

matter halos (Behroozi et al., 2019). Tens of thousands of satellites down to sub- L^* luminosities will be mapped and characterized. Thanks to deep, wide-field imaging surveys, like LSST, a 1M-object environmental survey at $z = 1-2$ may then be possible using improved photo- z s, strong priors on spectral types, and new machine-learning techniques to deliver *spectroscopic* redshifts (with $\lesssim 300$ km/s accuracy) at the lowest signal-to-noise possible (exposure times reduced by factors of 4–5).

1.4.3. *Internal structure of galaxies at intermediate redshift.* MaNGA (Bundy et al., 2015) and other large IFU surveys are defining the $z = 0$ benchmark for how internal structure is organized across the galaxy population. To understand and test ideas for how this internal structure emerged, we require spatially-resolved observations at $z = 1-2$, just after the peak formation epoch. Indeed, Keck has helped pioneer such observations (e.g., Erb et al., 2004; Miller et al., 2011; Law et al., 2009). With only one galaxy observed at a time, samples have so far been limited to a few hundred sources; however, FOBOS will obtain resolved spectroscopy for thousands of galaxies using its IFU-mode with a 25 deployed IFUs. Bright optical emission-line tracers for this unprecedented sample of galaxies will reveal their gas-phase and kinematic structure. Stacking restframe $\lambda \approx 4500$ spectra will enable radial stellar population analyses to constrain how stellar components formed and assembled. Although initially limited to coarse spatial scales, ground-layer adaptive optics (GLAO) in combination with FOBOS would be transformative for this science. A corrected FWHM of 0.2-0.3 arcsec would enable fine-sampling IFUs to probe smaller galaxies and study sub-structure on 1–2 kpc scales.

1.4.4. *The dark and luminous content of nearby galaxies.* Environmental effects and evolutionary processes evident at higher redshift have consequences that can be tested in present-day galaxies. Using globular cluster and planetary nebulae as tracers, FOBOS will dramatically advance dynamical studies of nearby galaxies with $M_*/M_\odot \lesssim 10^{11}$, capturing the majority of the ~ 1000 GCs located within ~ 50 kpc of typical hosts (see Harris et al., 2013) and tightly constraining their dark matter halos. FOBOS’s multi-IFU mode will additionally provide powerful insight on the origin of dwarf galaxies, both compact and ultra-diffuse (UDGs), in the field and in nearby clusters like Coma and Virgo.

1.5. Dramatically Enhancing Cosmological Probes.

1.5.1. *Dark Energy Probes via Precision Cosmic Distances.* Panoramic imaging surveys (e.g., LSST, Euclid, and WFIRST) are seeking to constrain the dark-energy equation-of-state at $z \lesssim 1$ through measurements of angular correlations of galaxy positions, their gravitational lensing shear, and the cross-correlation between the two. These surveys rely on photometric redshifts (“photo- z s”), whose uncertainties and potential biases are the major limitation and source of systematic error in these efforts (Newman et al., 2019; Mandelbaum et al., 2019). Newman et al. (2015) define a *spectroscopic* survey for photo- z training that would *increase the dark energy figure-of-merit in LSST by 40%*. The survey program is ideally matched to FOBOS. It requires 10 independent fields, each 20 arcmin in diameter, with a sampling density of 6 arcmin $^{-2}$, and the ability to go very deep ($i_{AB} < 25.3$). FOBOS’s lack of a “redshift desert” further eliminates the need for expensive, space-based² near-IR spectroscopy to train photo- z s with $z > 1.5$. Highly accurate photo- z s will enable science applications that go beyond cosmology.

²Ground-based near-IR spectroscopy is too contaminated by sky-line emission to provide spec- z s at the required level of completeness (Newman et al., 2015).

1.5.2. *Cosmology with LBG–CMB cross correlation.* High-S/N CMB maps from next-generation CMB observatories (e.g., Simons Observatory and CMB-S4) will provide a cosmic “reference background” for measurements of gravitational lensing induced by matter along the line of sight. After cross-correlating with Lyman Break Galaxy (LBG) samples, a relatively flat lensing “kernel” with power at $z = 2\text{--}5$ enables powerful constraints on the Inflation-sensitive matter power spectrum, Horizon-scale General Relativity, cosmic curvature and neutrino masses, and early Dark Energy (Ferraro & Wilson, 2019). Wilson & White (2019) explore these constraints in detail and highlight the need for spectroscopic determination of accurate redshift distributions for the employed LBG samples. FOBOS would address this need in two ways. First, several deep-drilling fields targeting ~ 1000 LBGs BX, u , g , and r drop-out candidates per pointing ($\sim 10,000 \text{ deg}^{-2}$) would establish the interloper rate and intrinsic redshift distribution of LBG samples to sufficient precision (this program would likely overlap with the photo- z program described above). Second, ~ 200 LBGs per pointing (2000 deg^{-2}) could be included as a background program when FOBOS observes other sources across the sky, eventually building a 50-100 deg^2 data set of sparse high- z spectroscopy for LBG dN/dz calibration via clustering redshifts (see Wilson & White, 2019).

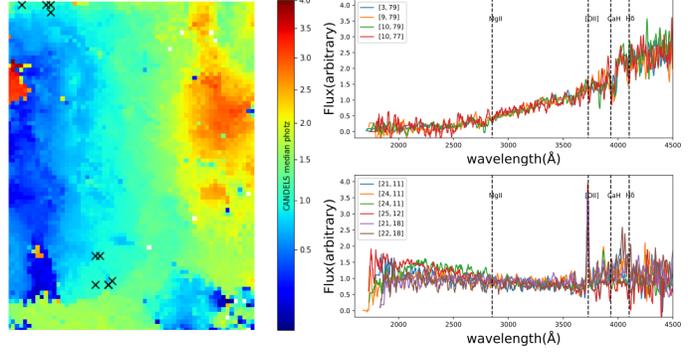


FIGURE 2. *Left:* A Self-Organizing Map (SOM; Kohonen, 1990) from Hemmati et al. (2018) relating LSST+WFIRST-like galaxy colors to redshift, z . FOBOS spectroscopic training samples can be optimally designed to populate/calibrate sparsely sampled regions. *Right:* Galaxy spectra from VVDS (Le Fèvre et al., 2005) in SOM locations marked by black crosses. More than just redshifts, the detailed similarity of spectral features of galaxies localized within the SOM demonstrates higher-level inferences (e.g. SFR) are possible given appropriate training samples from FOBOS.

1.6. **FOBOS as an ideal spectroscopic training instrument.** In all three science areas above, FOBOS offers significant advances by serving as the leading U.S. facility in providing spectroscopic *training* data. As machine learning techniques advance in the coming decade, spectroscopic “training” as a means of extracting the maximum information from billions of photometric sources across thousands of deg^2 becomes increasingly important. The required training samples at LSST depths will fill even the modest Keck focal plane with 10’s of thousands of sources. The key requirements are sensitivity and multiplex (not field-of-view). Emphasizing these, FOBOS will be an ideal training facility for LSST-era photometric redshifts (see Salvato et al., 2019), galaxy physical properties (e.g., Davidzon et al., 2019), and stellar parameters (e.g., Ting et al., 2018).

2. TECHNICAL DESCRIPTION

Mounted at the Nasmyth focus of Keck II Telescope at WMKO, FOBOS³ will be one of the most powerful spectroscopic facilities deployed in the next decade. FOBOS includes a compensating lateral atmospheric dispersion corrector (CLADC; Fig. 3) to ensure that target light from all wavelengths falls on allocated fibers while also correcting image aberrations at the edges of the 20 arcmin diameter Keck field. Each of the CLADC lenses is ~ 700 mm in diameter, the first two

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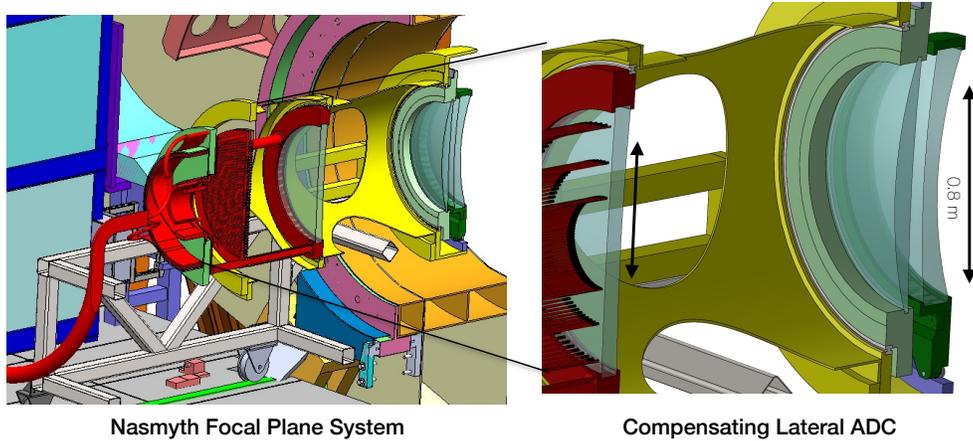


FIGURE 3. *Left*: Rendering of FOBOS focal plane system deployed at the Keck II Nasmyth port. *Right*: Rendering of the ADC and focal surface with Starbugs mounted (red cylinders).

are closely spaced with lateral relative motions of element one supplied by a single axis of motion acting along a curve equal to the radius of curvature of the first lens surface (1028 mm). The total offset of this lens is rather small at ~ 100 mm. The final CLADC lens translates by ~ 50 mm and tilts slightly to track the focal-plane shift. This last element acts to correct the telecentricity error into the fiber system and acts as the drive surface for the Starbug positioning system. Starbugs patrol a large on-sky area (~ 3 arcmin), enabling flexible and dynamic targeting configurations with adjacent fibers as close as 10 arcsec.

Starbugs, first proposed in 2004 (McGrath & Moore, 2004), and later perfected by AAO for use on TAIPAN (Staszak et al., 2016) are a truly remarkable fiber-positioning system. They move by *walking* on the focal plane using a pair of piezo tube actuators. A weak vacuum adheres the Starbugs to the surface of the field plate and provides the frictional normal forces needed to allow for the walking action of the piezo tubes. Positional feedback is provided by way of a camera imaging back-illuminated fibers on the focal plane. This system allows for a highly configurable focal plane both in terms of target densities and configuration of the fibers within an individual actuator. The Starbug payload can be both a single fiber or fiber-bundle IFU. The TAIPAN instrument, currently on sky conducting a large galaxy survey, is the proving ground for the readiness of this technology. It is worth noting that, although Starbugs are our preferred and baseline positioning technology, no aspect of FOBOS's current front-end design precludes using a zonal system, such as those used for MOONS, PFS, or DESI. The last element of the CLADC can be eliminated and replaced with a zonal actuator bed that conforms to the focal plane shape. Telecentricity can be maintained by alignment of the actuator axis to the incoming beam as is currently being designed for the SDSS-V robotic focal-plane system.

A total of 1800 fibers with $150\text{-}\mu\text{m}$ core diameter are deployed at the curved focal plane. Microlens fore-optics convert the $f/15$ Keck input beam to a faster $f/3.2$ focal ratio, which both demagnifies the entrance aperture ($\approx 0.9''$ diameter) and allows for a better coupling to the fiber numerical aperture that minimizes losses from focal ratio degradation (FRD). With the IFU mode deployed, a different set of lenslet array fore-optics would more finally sample the focal plane ($\approx 0.33''$). Accounting for 100 individual sky fibers and 10 7-fiber flux calibration bundles, 25 science IFUs, each comprised of 61 fibers, would deploy in this mode. The diameter of each 61-fiber bundle

corresponds to $3''$ on-sky. A single 61-fiber bundle would remain fixed at the field center in all FOBOS observing modes, enabling rapid target acquisition of transient sources.

The focal-plane plate rotates and translates to follow image positions as the telescope tracks across the sky. The fiber run is kept as short as possible to maintain high throughput at UV wavelengths (a 10 m Polymicro Silica fiber transmits $\sim 70\%$ and $\sim 85\%$ of light at 310 nm and 350 nm, respectively). Special care is given to stress-relief cabling to minimize instabilities (e.g., variable FRD) over the fiber run. To maintain the highest possible transition efficiency there are no connectors used within the fiber run. When FOBOS is not in use, the focal-plane unit detaches from the front-end, ADC module and its associated robotics, and it is stored with the spectrographs on the Nasmyth platform. This allows the ADC module to be transferred to any of the instrument park positions. All other Keck-II instruments can still be used without modification.

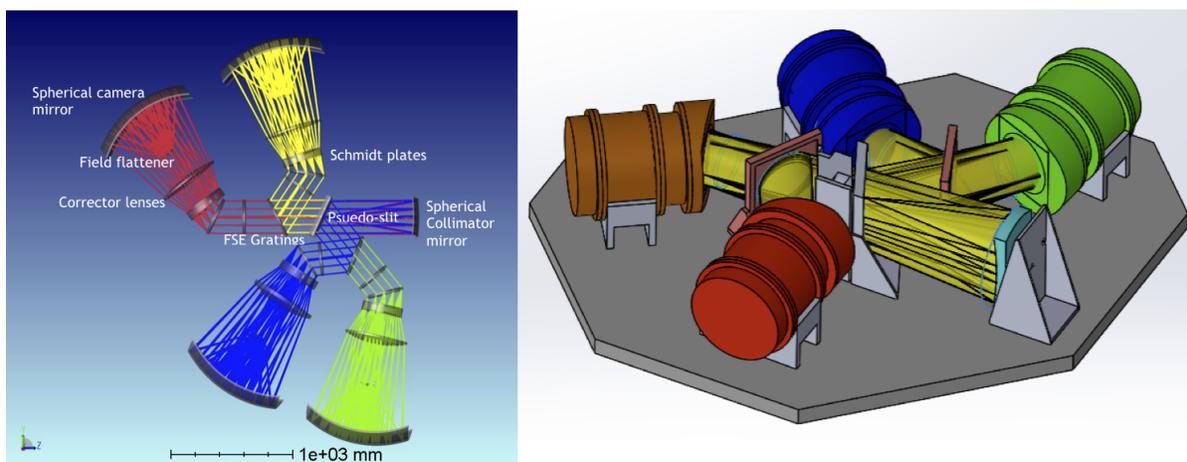


FIGURE 4. Optical design (left) and mechanical rendering (right) of a 4-channel FOBOS spectrograph employing catadioptric cameras. Light from a 600-fiber pseudo-slit strikes a collimating mirror and then passes back through subsequent dichroics before entering each grating-camera unit.

FOBOS's three identical spectrographs (Fig. 4) are each fed by a pseudoslit of 600 fibers. Each FOBOS spectrograph uses a series of dichroics to divide the 259 mm collimated beam into four wavelength channels, providing an instantaneous broad-band coverage from $0.31\text{--}1\ \mu\text{m}$. Fused-silica etched (FSE) gratings provide mid-channel spectral resolutions of $R \sim 3500$ at high diffraction efficiency in each channel. The dispersed light is focused by an $f/1.1$ catadioptric camera⁴ and recorded by an on-axis $4\text{k} \times 4\text{k}$ CCD mounted at the center of the first camera lens element. Unlike the mountable ADC module, the spectrographs are housed in a permanent temperature-controlled structure on the Nasmyth deck. The end-to-end instrument throughput peaks at 60% and is greater than 30% at *all* wavelengths.

FOBOS will include observatory level systems for precise instrument calibration using dome-interior screen illumination, a metrology system for accurate fiber positioning, and guide cameras for field acquisition and guiding. Initial deployment of the focal-plane will focus on a single-fiber format, with a secondary deployment of multi-format fiber bundles. Beyond FOBOS, future instruments could share the focal plane, integrating their fiber feeds to separate spectrographs optimized for higher spectral resolution, and/or different wavelengths (e.g., the near-IR). FOBOS

⁴Based on the camera design for the Multi-Object Optical and Near-infrared Spectrograph (MOONS) on the Very Large Telescope (VLT).

is ideal for taking full advantage of a future Ground-Layer Adaptive Optics capability. It also allows for testing advances in spectrometer design that may be critical to future spectroscopic facilities.

2.1. Technology Drivers. FOBOS will provide key capabilities in the near-term thanks to deployment at the existing Keck II telescope. It both carries a relatively modest cost compared to other proposed large-scale spectroscopic facilities (e.g., MSE, SpecTel) and helps lay the groundwork for their realization. Thus, while FOBOS will prove to be a valuable long-term investment for the W. M. Keck Observatory, it can also provide for invaluable technological development leading to efficiency and cost-cutting strategies for these larger facilities.

2.1.1. Starbugs fiber positioners. Starbugs are a positioning technology developed and deployed by Australian Astronomical Optics (AAO), which has partnered with our team to generate a conceptual design for use of Starbugs by FOBOS. The Starbugs positioning systems is highly attractive because of its flexibility both in terms of configuring a given set of fibers, as well as the prospect of exchanging different groups of Starbugs with different payloads and/or those that feed different spectrographs (e.g., high vs. low resolution). With such a flexible focal plane deployment, FOBOS can serve as a platform for cost-cutting technology development, which is not possible with fixed-format instruments like PFS and DESI. Starbugs are currently being tested on-sky with the TAIPAN instrument at the UK Schmidt Telescope and published results on their performance are expected in summer 2019.

2.1.2. Data Systems. A key to FOBOS's success with the development of robust data-reduction and data-analysis pipelines, building on the heritage of efforts within SDSS, DESI, and MaNGA. In particular, the FOBOS data-analysis pipeline (DAP) will take advantage of the fixed spectral format and common target classes to provide high-level data products, including Doppler shifts, emission-line strengths, and template continuum fits (cf., Westfall et al.; SDSS-IV MaNGA DAP). Planning will include development of user-friendly platforms built on the Keck Observatory Archive for serving raw data, reduced spectra, and DAP science products.

2.2. Current Status. FOBOS is currently in its conceptual design phase, building from a down-selection process as one of the designs for the Wide-Field Optical Spectrograph for TMT. Recently, FOBOS has been awarded Phase-A funding from WMKO Observatory, receiving a full design-phase endorsement from the Keck Science Steering Committee. These funds are devoted to completing the conceptual design in preparation for future funding proposals, particularly the NSF MSIP and MsRI calls.

2.3. Cost Estimates and Schedule. Cost estimates for FOBOS reflect its current development phase and are reported in Table 1 where available. Our conceptual-design-phase estimates have higher fidelity for the near-term phases of Preliminary Design and the beginning of Final Design. Where possible, costing efforts are based on quotes, and labor efforts are based on experience with similar systems developed by the institution responsible for a given sub-system. Our cost projections in combination with experience from other instruments place FOBOS in the category of a medium-scale ground-based instrument program suitable for MsRI-2 construction funding.

Nearly all costs prior to Final Design 2 are allocated to design efforts; however, a small amount is devoted to prototyping needed to mitigate risk in key systems. Our project execution plan divides Final Design into two phases to allow for a gate for long-lead-time contracts after a review in June of 2024, such as procurement and construction of the ADC optics. The Integration phase also

overlaps with the construction phase to allow for the facility system build-out at Keck Observatory and to allow for a phased deployment of the multiplexed focal-plane system. A full project review is scheduled at the end of each design phase. A pre-ship review will be held during integration prior to delivery of the first spectrograph. Smaller sub-system reviews will be held as required.

TABLE 1. Nominal Schedule and Cost Estimates for FOBOS

Phase	Start	End	Cost (2019 USD)	Fidelity
Conceptual Design	Q2 2018	Q1 2021	\$730k	Resource-loaded schedule with progress tracking
Preliminary Design	Q2 2021	Q2 2023	\$2.6M	Resource-loaded schedule
Final Design One	Q3 2023	Q2 2024	\$1.5M	High-level tasks with cost/effort estimates
Final Design Two	Q3 2024	Q2 2025	\$1.5M	High-level tasks with cost/effort estimates
Construction	Q3 2025	Q1 2027	TBD	Block schedule with low-fidelity cost/effort estimates
Integration	Q2 2026	Q3 2027	TBD	Block Schedule with low-fidelity cost/effort estimates
Commissioning	Q4 2027	Q1 2028	TBD	Block Schedule with low-fidelity cost/effort estimates

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