The Dark Energy Spectroscopic Instrument (DESI)

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ABSTRACT

The Dark Energy Spectroscopic Instrument (DESI) is a Stage IV ground-based dark energy experiment that will study baryon acoustic oscillations (BAO) and the growth of structure through redshift-space distortions with a wide-area galaxy and quasar spectroscopic redshift survey. The DESI instrument consists of a new wide-field (3.2 deg. linear field of view) corrector plus a multi-object spectrometer with up to 5000 robotically positioned optical fibers and will be installed at prime focus on the Mayall 4m telescope at Kitt Peak, Arizona. The fibers feed 10 three-arm spectrographs producing spectra that cover a wavelength range from 360-980 nm and have resolution of 2000-5500 depending on the wavelength. The DESI instrument is designed for a 14,000 sq. deg. multi-year survey of targets that trace the evolution of dark energy out to redshift 3.5 using the redshifts of luminous red galaxies (LRGs), emission line galaxies (ELGs) and quasars. DESI is the successor to the successful Stage-III BOSS spectroscopic redshift survey and complements imaging surveys such as the Stage-III Dark Energy Survey (DES, currently operating) and the Stage-IV Large Synoptic Survey Telescope (LSST, planned start early in the next decade).

Keywords: Dark Energy, multi-object spectroscopy, wide field corrector, redshifts, Mayall Telescope

1. INTRODUCTION

One of the biggest mysteries in cosmology today is what is causing the accelerating expansion of the universe. This so called Dark Energy could be a cosmological constant, a new long-range repulsive force, some modification to gravity or something we have not thought of yet. Experimentally we measure two major aspects of our universe, the expansion rate and the growth of structures such as galaxies and galaxy clusters. The Friedman equation tells us how the dark energy equation of state parameter w relates to the expansion rate of the universe. Thus by measuring the expansion rate as a function of red shift, as the universe is evolving, we can put constraints on dark energy.

DESI will measure the expansion of the Universe by observing the imprint of baryon acoustic oscillations (BAO) set down in the first 380,000 years of its existence. This pattern has the same source as the pattern seen in the cosmic microwave background (CMB), but DESI will map it as a function of cosmic time while measurements of the CMB only tell us about the scale when the universe was 380,000 years old. In the early universe acoustic (density) waves produced a peak in the clustering of matter. This peak evolved into the galaxies and galaxy clusters that we see today. It serves as a standard ruler whose length is fixed by measurements of the CMB. By measuring the positions and separations of galaxies as a function of redshift, we can measure how this standard ruler was stretched by the expansion of the universe. The DESI project will take the next step in studying the nature of the mysterious dark energy by measuring BAO over nearly the entire northern sky and over nearly the entire age of the universe.

The DESI survey area will overlap with the DES and LSST survey areas, which are primarily in the Southern hemisphere, but which have equatorial and northern ecliptic regions. The wide field spectroscopy provided by DESI is an ideal complement to the photometric surveys of DES and LSST. DESI will be a pathfinder instrument for the massive spectroscopic follow-up required for future large area imaging surveys such as LSST.

DESI builds on the success of previous surveys such as the Sloan Digital Sky Survey (SDSS, SDSS-II and SDSS-III/BOSS) as well as the Dark Energy Survey. The Dark Energy Community Planning Report (Rocky

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-III), commissioned by the Department of Energy Office of High Energy Physics, identified the need for a wide-field spectroscopic survey as part of their program to study dark energy. The DESI instrument on the Mayall 4m telescope, with its 3.2 deg. linear field of view, 5000 robotically actuated fibers and 10 high resolution spectrographs fulfills this need. Figure 1 shows a schematic of DESI on the Mayall. DESI is designed to measure the redshifts of roughly million galaxies and quasars in a 14,000 sq. deg survey. The resulting high precision map will cover the redshift range out to 3.5, shedding new light on the expansion history and growth of large scale structure in the Universe.

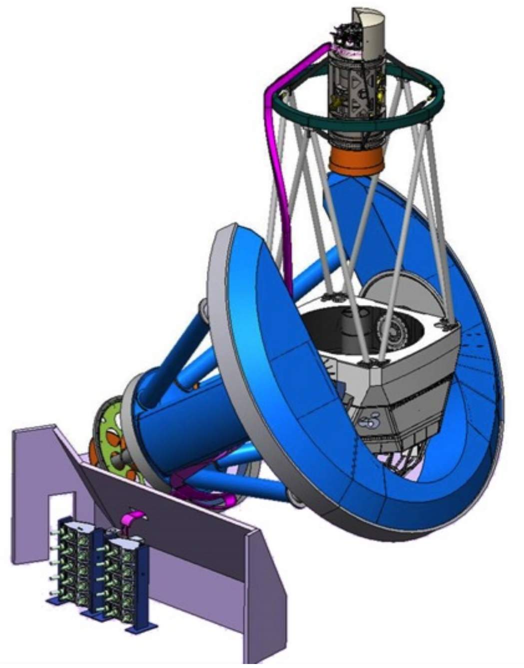

Figure 1. DESI on the Mayall telescope. The 5000 fiber positioner is located at the top of the prime focus cage under the cap (grey). The fiber bundles (purple) will cross the optical path in the shadow of the the support fins and be routed around the declination and polar axes allowing for telescope motions and then terminating at the spectrographs in the code room.

The DESI project follows a model similar to that used for the Dark Energy Survey by capitalizing on the availability of a wide field 4m telescope. The Dark Energy Survey (DES) collaboration built a new 3 sq. deg. 570 Megapixel imaging camera, DECam[1] to replace the prime focus cage and corrector of the Blanco 4m telescope. DECam had a very successful first light in Sept. 2012 and the 5000 sq deg. DES survey began in Sept. 2013.[2] Similarly the DESI collaboration is forming around the plan to replace the top end of the Mayall 4m telescope with a new wide field multi object spectrometry system. The Mayall and Blanco telescopes are twins, built from the same drawings, in the early 1970's, and many of the lessons learned from the DECam experience are being applied directly to the DESI project planing and execution.

The DESI project represents a merger of two early concepts proposed to the DOE/OHEP: Big-BOSS[3] (on the Mayall telescope at Kitt Peak) and DESpec[4] (on the Blanco telescope at CTIO in Chile). In early 2013 the newly formed DESI collaboration, led by Lawrence Berkeley National Laboratory (LBNL), performed analysis considering the various available sites for the survey and concluded that the best opportunity was provided by the Mayall telescope, which had the significantly more time available for a large survey. The Mayall is currently operated by NOAO with funding from NSF/AST. DOE/OHEP and NSF/AST are in the process of establishing agreements for funding and operations for DESI. The collaboration is in the process of forming and currently consists of 21 U.S. universities, 5 DOE national labs, 19 foreign institutions and over 180 scientists. The DOE Particle Physics Project Prioritization Panel (P5) gave DESI a favorable review in May 2014 and DOE has told the project to proceed to a Critical Decision 1 review in Sept. 2014. If the DOE funding is approved, DESI could begin operations in the 2018/2019 time frame and would take approximately 5 years to complete the 14,000 sq. deg. survey.

DESI made great progress in 2013 -2014, the optical design was reviewed and finalized, the first spectrograph was ordered, the fiber positioner technology was selected and orders for the lenses will be in place by the end of this summer.

Below we discuss the DES science and then describe the major systems of the instrument.

2. DESI SCIENCE

The DESI science program builds on the very successful BOSS survey which currently has the best measurements of Baryon Acoustic Oscillations (BAO). The BOSS survey is a third generation survey in the SDSS program (SDSS-III) and has established new techniques for extending the redshift range of the BAO measurements by using quasars and the Lyman-α forest.[5] BOSS has a 2.4m mirror, a 3.0 deg field of view, 1000 fibers and the survey covered over 8000 square degrees. More than 1.2 million galaxies and nearly a quarter million quasars were measured. The survey concentrated on the Luminous Red Galaxies (LRGs) in redshift range around 0.5, the time period when dark energy began to dominate and the expansion rate of the universe began to accelerate, and on quasars, to get to redshifts over 2 when the universe was dominated by dark mater. Figure 2 shows a plot of the expansion rate of the universe as a function of redshift with the redshift distributions from the BOSS survey superimposed.

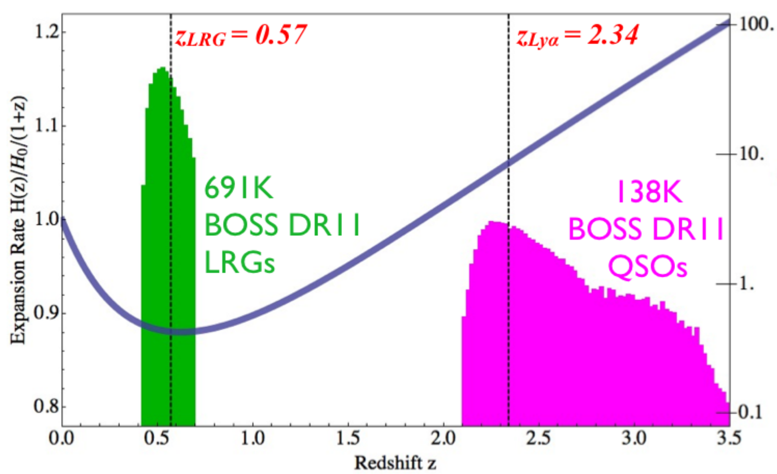

Figure 2. The expansion rate of the universe as a function of redshift (dark blue) with the BOSS redshift distributions superimposed.

The 14,000 sq. degree DESI survey provides at least an order of magnitude improvement over BOSS both in the volume of space it probes and the number of galaxies it will map. DESI will provide high precision measurements of the Universe's expansion rate over roughly 12 billion years, nearly the entire age of the universe. Spectroscopic targets will be selected in three classes from imaging data. We will measure 4 million luminous red galaxies (LRGs) up to z = 1.0, extending the BOSS LRG survey in both redshift and survey area. To probe the Universe out to even higher redshift, DESI will target roughly 23 million bright [O II] emission line galaxies (ELGs) up to z = 1.7. Approximately 2 million quasars will be targeted both as direct tracers of the underlying dark matter distribution and, at higher redshifts ($2.2 < z < 3.5$), for the Ly-α forest absorption features in their spectra, which will be used to trace the distribution of neutral hydrogen. In total roughly 30 million galaxy and quasar redshifts will be obtained to measure the matter density in the universe and track the BAO feature as it evolves with the expansion of the universe. Figure 3 shows the number of targets of each type and the redshift range they will cover. The DESI map of the underlying matter distribution will also address other science topics such as redshift space distortions and put constraints on the mass of the neutrinos.

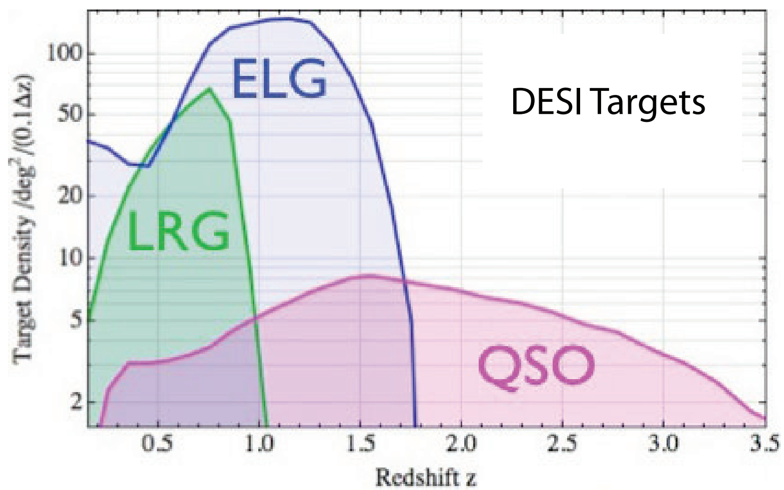

Figure 3. DESI target samples and the redshift ranges they will cover.

By measuring the BAO feature over the entire redshift range DESI will produce a world leading survey of the cosmic distance scale. In Figure 4 left panel we show the expected uncertainty in DESI measurement of the expansion rate of the universe as a function of redshift. DESI will constrain $H(z)$ to better than 0.3% statistical uncertainty and better than 0.2% systematic uncertainty. The panel on the right shows how the DESI measurements will compare to other current and future BAO surveys. DESI will far exceed other ground based BAO projects and will be competitive with future satellite projects.

3. THE DARK ENERGY SPECTROSCOPIC INSTRUMENT

The DESI instrument is designed to meet the key science goals within the operational requirements. The primary drivers of the design are

- 14,000 deg^2 BAO/Redshift Space Distortion redshift survey.
- Targets are 30 million galaxies comprised of LRGs, ELGs, QSO tracers, and Ly-α QSOs.
- The S/N for ELGs [O II] detection greater than 7 for a flux of 8×10^{-17} erg/s/cm^2.

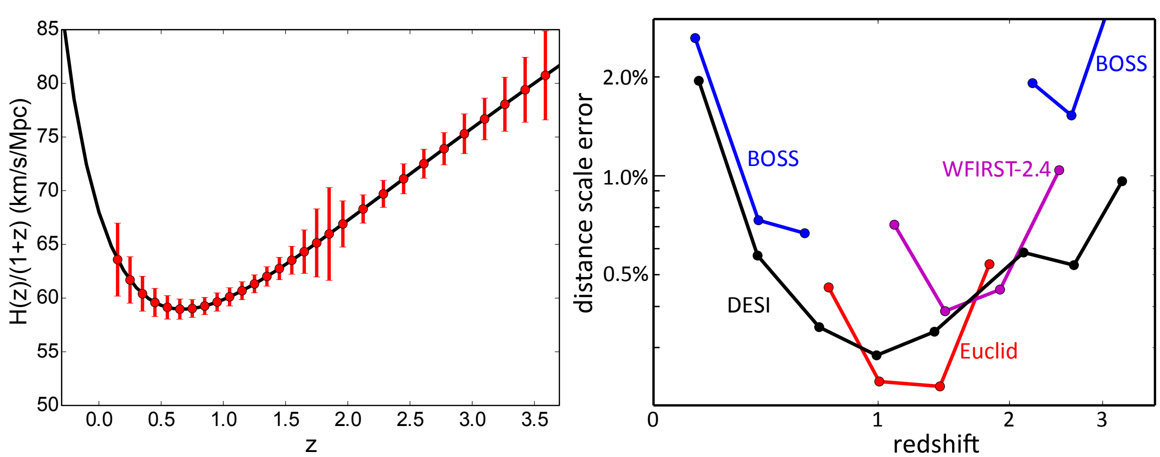

Figure 4. Expansion rate of the Universe as a function of redshift. The left plot shows the expected DESI uncertainties as a function of redshift and the right plot shows the fractional error presented in comparable bins for DESI, BOSS, Euclid, and WFIRST. DESI will provide the best measurements over much of the region and is competitive with space-based missions, which will come later.

- Spectral range of 360–980 nm.
- Spectroscopic resolution for redshift error (precision and accuracy) $< 0.0005(1+z)$: >1500 for λ >360 nm and longer, >3000 for λ >555 nm, and >4000 from λ >656 nm.
- Fiber density ∼700 per square degree.
- Field of view (effective) not less than 7.5 square degrees.
- Survey duration of 5 years for 14,000 deg^2 survey, including 6 months commissioning and validation.

Performing a wide, deep spectroscopic survey of a large volume of the Universe in a five-year survey requires a high throughput spectrograph capable of observing thousands of spectra simultaneously. The DESI project is designed to achieve these ambitious goals. The instrument components are 1) prime focus corrector optics to achieve a wide field of view, 2) focal plane with robotic fiber positioners, 3) fiber optics cable management system, 4) spectrographs, 5) a real-time control and data acquisition systems, and 6) a data management system that inputs raw data from the detectors and produces calibrated spectra useful for cosmological investigation.

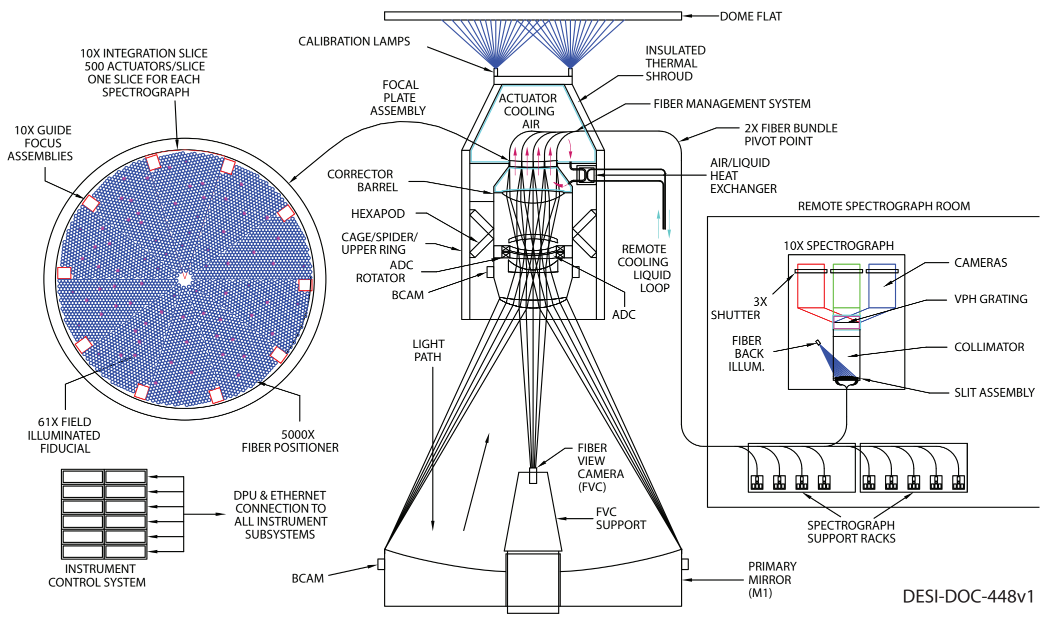

Figure 5. Block diagram of the DESI system. The focal plane is divided into petals that each contain 500 fiber positioners and a guide and focus sensor. The fibers for each petal are bundled into a jacketed cable and then routed down the telescope to a three armed spectrograph located in the Coudé room

Figure 1 showed DESI as installed on the Mayall telescope. Figure 5 shows a block diagram of the essential DESI components. The DESI lenses and ADC are mounted in a large steel barrel which is attached to the prime focus cage with a hexapod. The focal plane is attached the the back end of the optical corrector as a single unit. Internally the focal plane is divided into petals that each contain 500 fiber positioners, fiducial fibers and a guide and focus sensor. The fibers for each petal are bundled into a jacketed cable and then routed down the telescope to a three armed spectrograph located in the Coudé room. The electronics used to control the fiber positioners are located behind the focal plane and are enclosed in a cap for thermal management. The fibers tips of the focal plane can be illuminated from the point where they enter the spectrographs housing. A fiber view camera located in the center of the primary mirror will take pictures of the illuminated fiber tips to confirm/direct the fibers to their desired locations. Below we describe each major system in more detail.

The DESI optical design, shown in Figure 6(left),[6] was extensively reviewed and finalized over the past year. The design contains 4 large fused silica lenses (C1-C4). C1 and C4 are over 1 m in diameter and the focal plane is 0.81m in diameter. The two smaller lenses have aspheric surfaces on one face and all other surfaces are spherical. The atmospheric Dispersion Corrector (ADC) consists of two spherical prisms that counter-rotate. The ADC lens material is N-BK7. The total mass of the lenses, including the ADC, is 863kg.

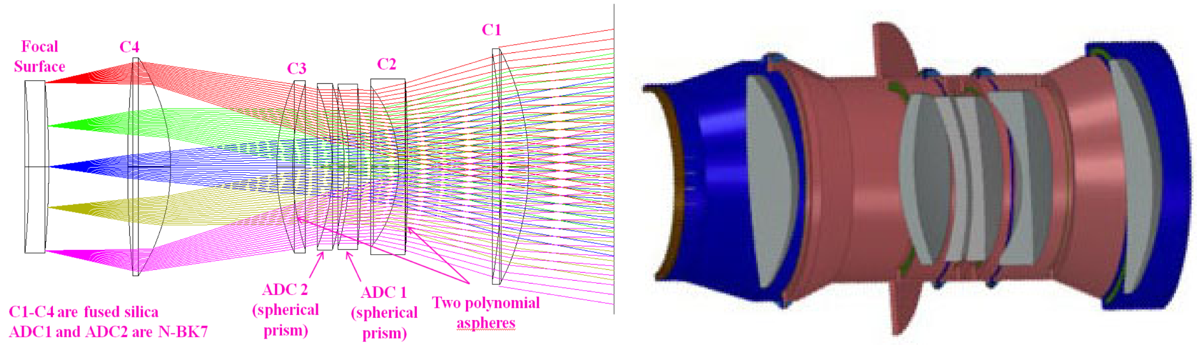

Figure 6. Left: DESI final optical design. the largest lens, C1, is 1.14m in diameter and the total mass of the lenses in the design is 863kg. The two smaller fused silica lenses have aspheric surfaces on one face, with all other silica surfaces spherical. Right: Optical elements assembled into the corrector barrel.

The lenses will be glued into circular Invar “cells” using custom designed RTV pads. The cells are bolted and pinned to precision surfaces in the rigid steel barrel that provides structural support for the entire corrector. The cells contain flexures to compensate for different coefficients of thermal expansion between the lenses and the barrel. Figure 6(right) shows the lenses in the barrel structure.

The DESI focal plane system is shown in Figure 7.[7] A structural shroud extends beyond the focal plane and bolts to the end of the corrector barrel. The shroud also contains holes for air cooling of the focal plane. The focal plane consists of 10 petals. Each petal can be independently removed or installed. The fibers, actuators, electronics and fiber spool box all fit within the shadow of each petal. The entire focal plane system is enclosed for thermal management.

At the end of May 2014 the DESI project held a review of the available fiber positioner technologies. The design selected is shown in Figure 8. These actuators use two 4mm brushless DC motors; one drives the θ rotation and one drives the eccentric ϕ rotation. The fiber threads gently through the actuator and is attached to the tip (the hole shown in the ϕ arm in the figure). The motor drive electronics are contained on a small printed circuit board that fits in the shadow of the actuator. The actuators have threads that screw into the

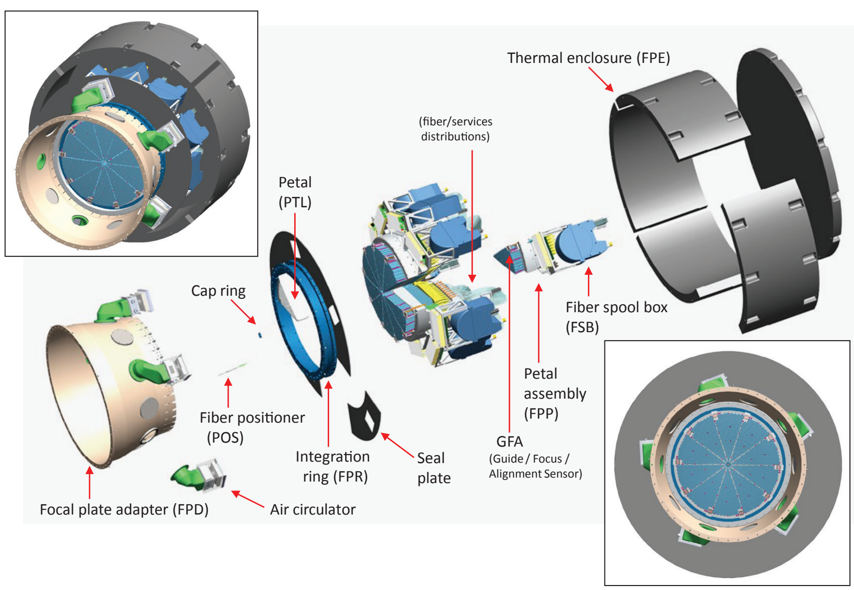

Figure 7. DESI focal plane system.

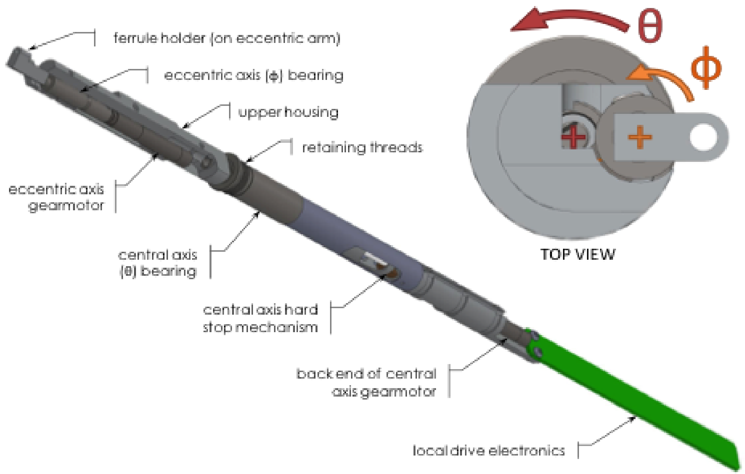

Figure 8. DESI theta-phi actuator.

focal plane.

A fiber system[8,9] will transport the light from the galaxies to the ten spectrographs with as little attenuation and f/# degradation as possible. Careful planning for the movement of the focal plane for focus and alignment as well as for the motion of the telescope is part of the design.

The spectrograph design was also finalized this year[10] and is shown in Figure 9. The three arms cover wavelength range from 360 nm to 980 nm with resolution R $= \lambda/\Delta\lambda =$ 2000–5500 depending on wavelength, meeting or exceeding the DESI requirements.

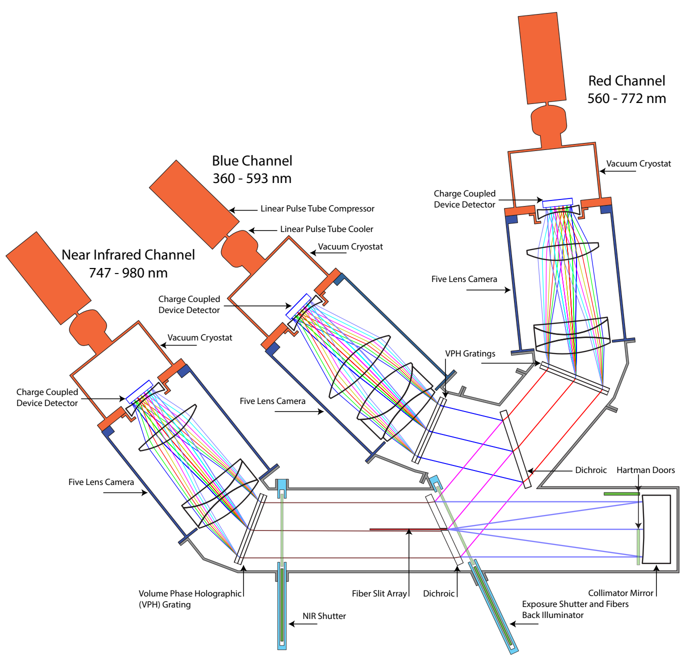

Figure 9. DESI three channel spectrograph

4. CONCLUSIONS

Following a favorable endorsement by the P5 committee, DOE/OHEP has told the DESI project to proceed to the next step in the approval process, a CD-1 review in Sept. 2014. Most of the DESI instrument designs are final or near final. LBNL won a grant from the Moore foundation and this is providing critical early funding for the 1st spectrograph and the lenses. The collaboration is in the process of forming and non-US collaborators are receiving R & D support and pursuing additional funding for the project. DOE/OHEP and NSF/AST are in the process of forming agreements about operation of the Mayall telescope during the DESI survey. Current projections are that installation on the Mayall could begin in early FY2018.

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