

The MegaMapper
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The MegaMapper: A Stage-5 Spectroscopic Instrument Concept for the Study of Inflation and Dark Energy

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ABSTRACT

In this white paper, we present the MegaMapper concept. The MegaMapper is a proposed ground-based experiment to measure Inflation parameters and Dark Energy from galaxy redshifts at $2 < z < 5$. In order to achieve path-breaking results with a mid-scale investment, the MegaMapper combines existing technologies for critical path elements and pushes innovative development in other design areas. To this aim, we envision a 6.5-m Magellan-like telescope, with a newly designed wide field, coupled with DESI spectrographs, and small-pitch robots to achieve multiplexing of 26,100. This will match the expected achievable target density in the redshift range of interest and provide a 15x capability over the existing state-of the art, without a 15x increase in project budget.

1 Introduction & Objectives

The mechanisms driving the accelerated expansion of the Universe in its very first moments (Inflation) and at late times (Dark Energy) represent some of the most important open problems in fundamental physics, and have been the subject of several of the Snowmass Community Science White Papers [e.g., 1–5]. We refer readers to those papers, and the questions therein, which have informed the development of the MegaMapper concept. Below, we sketch in brief the concept itself and how this concept aims to address these open problems with a singular platform. At root, the fundamental challenge for future spectroscopic experiments is mapping speed (at fixed spectroscopic fidelity). The MegaMapper concept combines a very wide field, a large primary aperture, and a densely packed focal plane to solve the next order of magnitude in the Mapping Speed progression. The main principles that guide the development of the MegaMapper concept are that 1) mapping speed envisioned for the next decade should aim for order-of-magnitude transformative change (see Figure 1), and 2) the development of projects of this nature should endeavor to remain “mid-scale” as long as practical in order to efficiently benefit from technical innovation, reduce project risk, and control cost and schedule.

1.1 Cosmology and Fundamental Physics

Primordial non-Gaussianity [6] has been identified as one of the most powerful tools to study Inflation and the origin of the primordial fluctuations. Although the simplest inflationary models predict Gaussian initial conditions, large classes of models predict deviations from Gaussianity that leave specific imprints on the galaxy power spectrum and bispectrum [6, 7], thus probing physics at scales inaccessible to Earth-based colliders. Distinguishing multi-field from single-field inflation requires bounds on the “local” non-Gaussianity parameter to be considerably better than $\sigma(f_{NL}^{\text{local}}) \approx 1$, or about an order of magnitude improvement over current constraints [8]. Moreover, a model independent reconstruction of the spectrum of matter perturbations will significantly improve our understanding of

the primordial fluctuations, as well as any oscillation or feature in the primordial power spectrum, often affected by the physics of inflation [9, 10].

Our understanding of Dark Energy [11] will greatly benefit from measuring the expansion and growth of fluctuations throughout cosmic history. A lever arm that extends from low redshift (Dark Energy era) to high redshifts (matter domination era) will tightly constrain large classes of theories, and test possible modifications to General Relativity. Moreover, precision measurements of the matter power spectrum will provide tight constraints on Early Dark Energy models, providing a few percent measurement out to $z \sim 10^5$ [5, 10].

The large volume available at $z > 2$ will increase the number of modes measured by over an order of magnitude over current experiments, opening up an uncharted territory with huge discovery potential. Over the next decade, the Rubin Observatory’s Legacy Survey of Space and Time (LSST) [e.g. 12] will begin to enable hundreds of millions of tracers to be targeted for the MegaMapper.

The increased mapping speed by more than one order of magnitude, together with targets selected from the LSST imaging, will allow us to observe a high-redshift sample at $2 \lesssim z \lesssim 5$. The large volume available over this redshift range will allow the MegaMapper to explore primordial physics to unprecedented precision, beyond the CMB cosmic variance limit [5]. Dramatic improvements in the constraints on Inflation and Dark Energy [5, 10, 13] are possible, while relaxing assumptions such as a power-law primordial power spectrum [9, 14]. LSST imaging will enable the selection of ≈ 100 million spectroscopic targets spanning this redshift range. These targets are a combination of massive galaxies and highly star-forming systems, both of which can be efficiently selected from broad-band photometric surveys [15].

The MegaMapper represents a cost-effective, low-risk version of such a survey, capable of achieving the stated science goals using proven technologies. Simultaneously, experience from the pioneering SDSS suite of surveys demonstrates that such a facility would confer a tremendous opportunity for ancillary science explorations that help answer a broad array of astronomical questions from the formation of the Milky Way to the evolution and growth of galaxies.

Possible sites for the MegaMapper include Las Campanas Observatory (Chile), Cerro Tololo Observatory (Chile), San Pedro Martir (Mexico) and Kitt Peak National Observatory (Arizona). The Chilean sites would have full overlap with LSST imaging, whereas the northern sites would be limited to 15,000 sq. deg. of suitable extragalactic overlap in the $-30 < \delta < +30$ equatorial region.

1.2 Cosmology Science Forecasts: Inflation and Dark Energy

In [13] we have identified two samples, a more optimistic “idealized” sample based on the LSST target density of Lyman- α emitters and Lyman-Break galaxies, and a “fiducial” sample, based on conservative redshift success rates and assumptions about line strengths (see [13] for the sample specifications and [15] for background about selection and sample

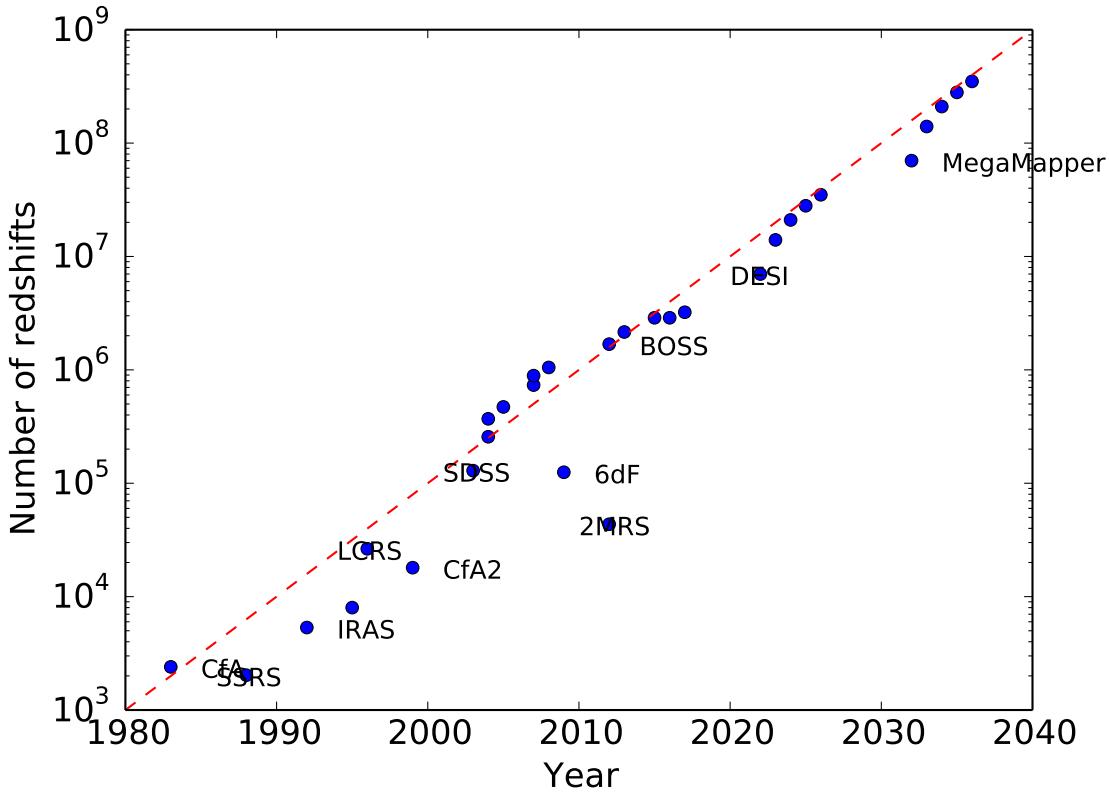


Figure 1: Number of galaxy redshifts as a function of time for the largest cosmology surveys. The dotted line represents an increase of survey size by a factor of 10 every decade. Fielding the MegaMapper in ten years maintains this pace into the 2030s, and enables the Inflation and Dark Energy measures proposed in this and other white papers.

properties).

We have found that both samples can cross the theoretical threshold $\sigma(f_{NL}^{\text{local}}) \lesssim 1$, from measurement of the galaxy power spectrum on large scales, surpassing the current CMB bounds by an order of magnitude [10, 13]. Potentially large improvements are possible when including the analysis of the bispectrum. Improvements by a factor of two or larger over the current bounds are also expected for the equilateral and orthogonal shapes [13]. Particular care should be taken in the telescope and survey design to control systematics to allow such precise measurements of primordial non-Gaussianity.

Using a combination of Redshift-Space Distortions (RSD) and Baryon Acoustic Oscillations (BAO), the fraction of Dark Energy Ω_{DE} can be measured to better than 1% all the way to $z \approx 4.5$ for the “idealized” sample, and better than 2% up to $z \approx 5$ for the “fiducial” sample (see Figure 1 in [13]). Other notable improvements include a factor of two better

determination of the spatial Curvature (compared to DESI + Planck), and a factor of $\gtrsim 2.5$ improvement in the Dark Energy figure of merit (Table 4 in [13]). Early Dark Energy (EDE) has been proposed as a solution to the Hubble tension [16]. MegaMapper will be able to constrain the fraction of EDE to better than 2% all the way to $z \sim 10^5$ [10], when the Universe was only a few years old, definitely testing this hypothesis, and more generally providing percent-level expansion constraints throughout cosmic history.

Table 1: Survey speeds for multi-fiber spectrographs as measured by the product of the telescope clear aperture, number of fibers and losses from mirror reflections. This speed assumes a dedicated facility, which would not be possible in all cases. Keck/FOBOS[17], MSE[18], SpecTel[19] and MegaMapper[20] are proposed experiments. LSSTspec[21, 22] is a notional number using MegaMapper positioners on the LSST focal plane, if optical design limitations could be overcome injecting f/1.2 light into fibers.

Instrument (year)	Primary/m ²	Nfiber	Reflections	Product	Speed vs. SDSS
SDSS (1999)	3.68	640	0.9 ²	1908	1.00
BOSS (2009)	3.68	1000	0.9 ²	2980	1.56
DESI (2020)	9.5	5000	0.9 ¹	42,750	22.4
PFS (2023)	50	2400	0.9 ¹	108,000	56.6
4MOST (2023)	12	1624	0.9 ²	15,800	8.3
DESI-Upgrade (2027)	9.5	11,250	0.9 ¹	96,200	50.4
MegaMapper	28	26,100	0.9²	590,000	309.
Keck/FOBOS	77.9	1800	0.9 ³	102,000	53.6
MSE	78	3249	0.9 ¹	228,000	119.
LSSTspec	35.3	8640	0.9 ³	222,000	116.
SpecTel	87.9	15,000	0.9 ²	1,070,000	560.

Table 2: Survey speeds as measured by the raw product of collecting area and field-of-view. This is the appropriate metric for a wide-area survey with sparse targets. Even without taking full advantage of multiplexing, the MegaMapper survey speed is competitive with larger telescopes owing to its large field-of-view.

Instrument (year)	Primary/m ²	FOV/deg ²	Reflections	Product	Speed vs. SDSS
SDSS (1999)	3.68	7.06	0.9 ²	21.0	1.00
BOSS (2009)	3.68	7.06	0.9 ²	21.0	1.00
DESI (2020)	9.5	8.04	0.9 ¹	68.7	3.27
PFS (2023)	50	1.33	0.9 ¹	59.9	2.85
4MOST (2023)	12	4.90	0.9 ²	58.8	2.80
MegaMapper	28	7.06	0.9²	160.	7.62
Keck/FOBOS	77.9	0.087	0.9 ³	4.94	0.23
MSE	78	1.52	0.9 ¹	107.	5.10
LSSTspec	35.3	9.60	0.9 ³	247.	11.76
SpecTel	87.9	4.91	0.9 ²	350.	16.65

1.3 Additional Science Opportunities

The facility constructed in pursuit of the cosmology program described above also serves a broad range of additional astrophysical and cosmological objectives. Some of these would be addressed coincident with the 5-year cosmology key project, while others could be pursued after completion of that project by the broader community. Some of these science cases have been articulated in the National Academy of Sciences “Astro 2020” report. We summarize here the synergies of the MegaMapper with the recommendations of Astro2020 here.

1.3.1 Maximizing the community investment in LSST

A wide-field spectroscopic survey will greatly enhance the LSST science returns, as identified by several Astro 2020 science white papers [23–25]. Calibration of photometric redshifts is possible over the whole range of LSST sources through cross-correlation techniques with the spectroscopic sample. A large overlap in survey area will enable a reduction in the statistical errors to meet the stringent LSST requirements [23]. The availability of a large overlapping spectroscopic sample will allow cross correlation of these galaxies with the faint LSST sources to better constrain the Intrinsic Alignment effect in weak lensing measurements. Moreover, a combination of lensing amplitude provided by LSST, together with growth measurements through RSD can provide a powerful test of General Relativity on cosmological scales. Finally, the MegaMapper would provide redshifts for strong gravitational lenses and type Ia supernovae discovered in LSST, allowing their cosmological interpretation. **Wide-field spectroscopy is therefore a keystone for fully extracting the information content from other cosmological methodologies.**

1.3.2 The Milky Way as a Dark Matter Experiment

The MegaMapper, with its tremendously capable focal plane, will be a key complement to the astrophysical studies of Dark Matter [25–27]: by measuring the velocity dispersion of faint Milky Way satellites, the mass and density can be inferred and compared to theoretical predictions, in an environment where baryon effects are expected to be minimal. Similarly, the perturbations and gaps in the Milky Way stellar streams created by encounters with Dark Matter substructure create a characteristic velocity signal that can be measured with spectroscopy to determine the perturber mass [26]. Moreover, the merger dynamics in galaxy clusters can be studied, providing constraints on self-interacting Dark Matter [28]. In particular, the MegaMapper concept is already inspiring cosmologists to think about new methodological frameworks (beyond “streams” and “dwarf galaxies”) to consider more comprehensive dark matter experiments that can be done in the Milky Way.

Additionally, of great interest in the modern era and particularly with the successful launch of the James Webb Space Telescope, the MegaMapper can enable the industrial, wide-field study of galaxy evolution to $z \sim 2$ and stellar population and kinematics and dense tomography of the intergalactic medium [29]. While it is beyond the scope of what

is presented here, future instrumentation on such a facility in the post-survey period could enable a tremendous range of science from planet to galaxy formation and evolution. The concept thus represents an *enabling platform* in the spirit of the “SDSS-DESI” family of projects.

2 Technical Overview

The overall MegaMapper design seeks to optimize survey speed with a judicious choice of telescope aperture and instrument multiplexing. A new set of optical models achieves a speed (as measured by $A \cdot \Omega$) that is difficult to match with either smaller or larger telescopes (see Table 1). The overall telescope design is nearly identical to the existing Magellan 6.5-m telescopes, although the preferred design modifies the central hole to be larger to accommodate the wider corrected field of the new optical design. The instrument can accommodate a multiplexing of 26,100 and would feed between 600 and 675 fibers to each DESI spectrograph. 16 of these spectrographs already exist for the DESI and SDSS-V projects (see [30] and [31]), with another 23 to 28 spectrographs required for the full capability of the Stage-5 MegaMapper instrument (See Figure 2).

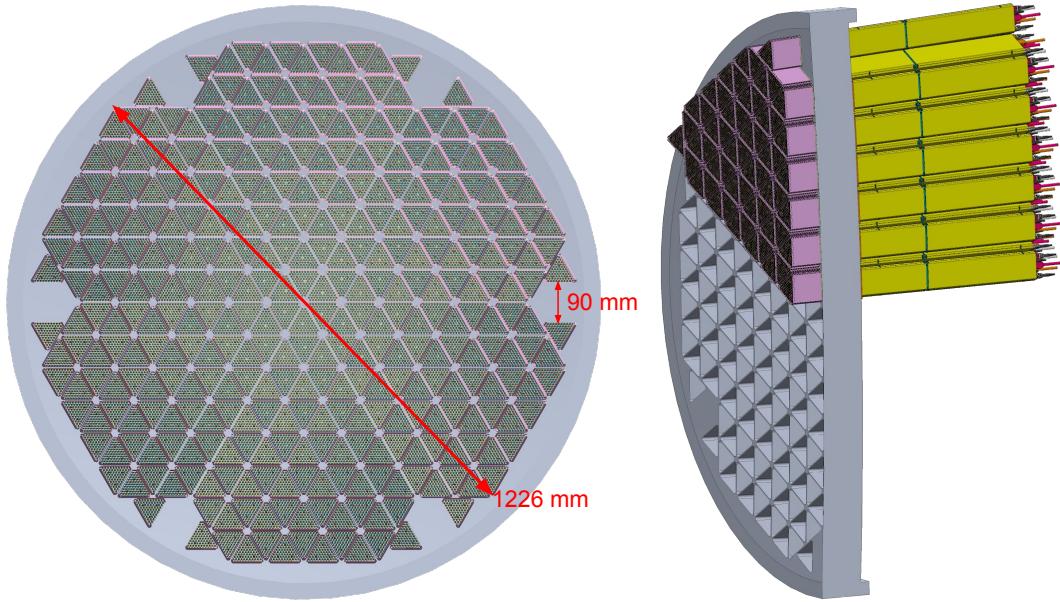


Figure 2: Focal plane layout for 348 fiber robot rafts (with 26,100 robots) on the MegaMapper focal plane. The triangular rafts offer mechanical stiffness, and could be individually inserted from the backside of the circular mounting plate. The six unpopulated locations at the edge of the focal plane are reserved for guide/focus cameras.

Telescope:

The telescope concept is based on the highly successful Magellan telescope design. This

constitutes a lightweight, honeycomb structure, 6.5 m borosilicate glass primary mirror built by the University of Arizona Mirror Lab. A baseline design is considered that adopts the same optical prescription as Magellan I and II (i.e., a f/1.25 paraboloid), equipped with a 2.4 m hyperbolic secondary mirror (\sim 70% larger in diameter than the current f/11 Gregorian secondaries), and a 5-lens wide field corrector that provides a 3.0 deg diameter field-of-view on a Cassegrain focal plane fed at f/3.6 (see Figure 4). An ADC is designed as part of the corrector. The first and largest element in the corrector is 1.8 m in diameter, with the other lenses also being meter sized. The large secondary and sky baffles imply a central obscuration of \sim 20% of the area of the primary mirror, significantly larger than the \sim 5% obscuration in the current Magellans but still less than either SDSS or DESI. This baseline design requires a larger central hole in the primary mirror than the 1.3 m hole in Magellan I and II, either by enlarging the central hole in an existing mirror or casting a new mirror with a custom mold.

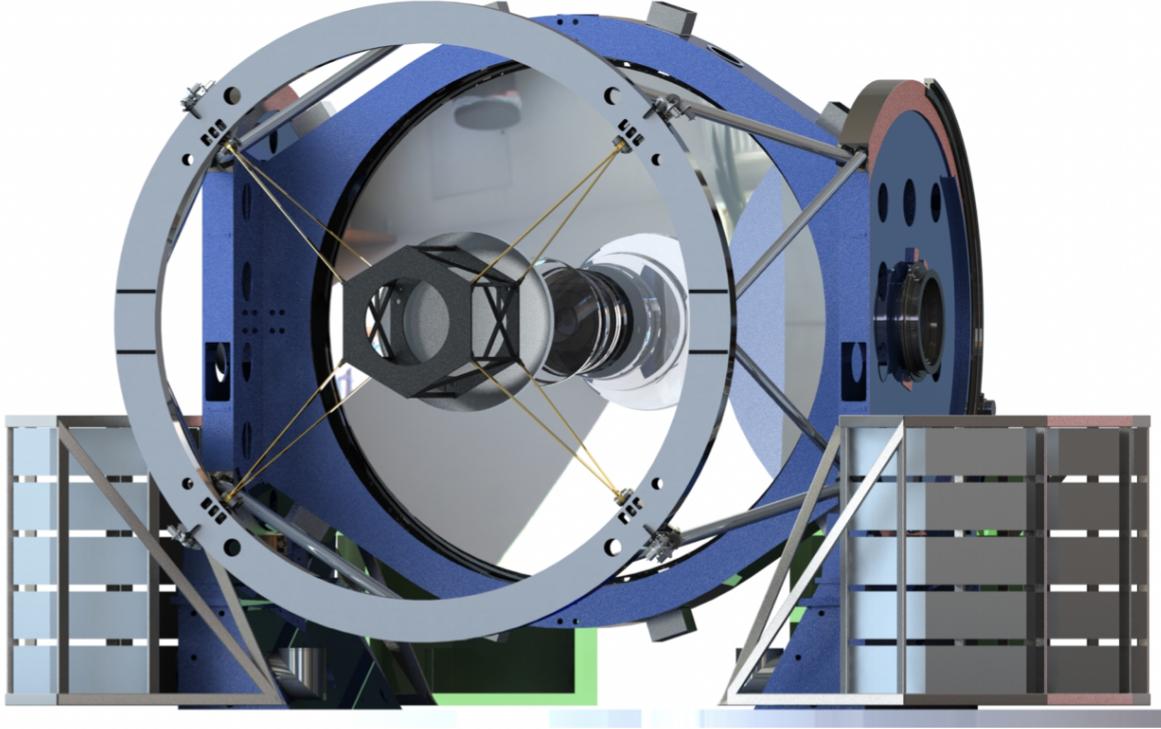


Figure 3: Rendering of the Magellan-style telescope with the secondary mirror and 5-element corrector, pointed towards the horizon. The spectrographs are parked on the base with a fiber run that is substantially shorter than the 51-meter fiber run for DESI.

The f/3.6 telecentric focal plane has a diameter of 1230 mm, which at a plate scale of 0.113 mm/” corresponds to a 3.0 deg diameter FOV. Figure 5 presents spot diagrams at different zenith angles for the telescope’s preliminary optical design described above, with $< 23 \mu\text{m}$ rms radius ($\sim 0.4”$ FWHM on sky) across the full FOV, which has a maximum of 2.7% vignetting at the field edge. At this platescale, a 107 μm optical fiber (identical to the

DESI fibers) subtends a diameter of 0.94" on the sky, which is near the optimal fiber size for point sources or compact, high-redshift galaxies in the sky-noise limit.

The telescope mount, enclosure, and auxiliary facilities could be identical to the current Magellan design. However, particular sub-systems would be redesigned and updated. Figure 3 shows the MegaMapper in the Magellan CAD. Some subsystems would benefit from advances of technology since the Magellan 1 & 2 builds, in particular for the sensor and control systems.

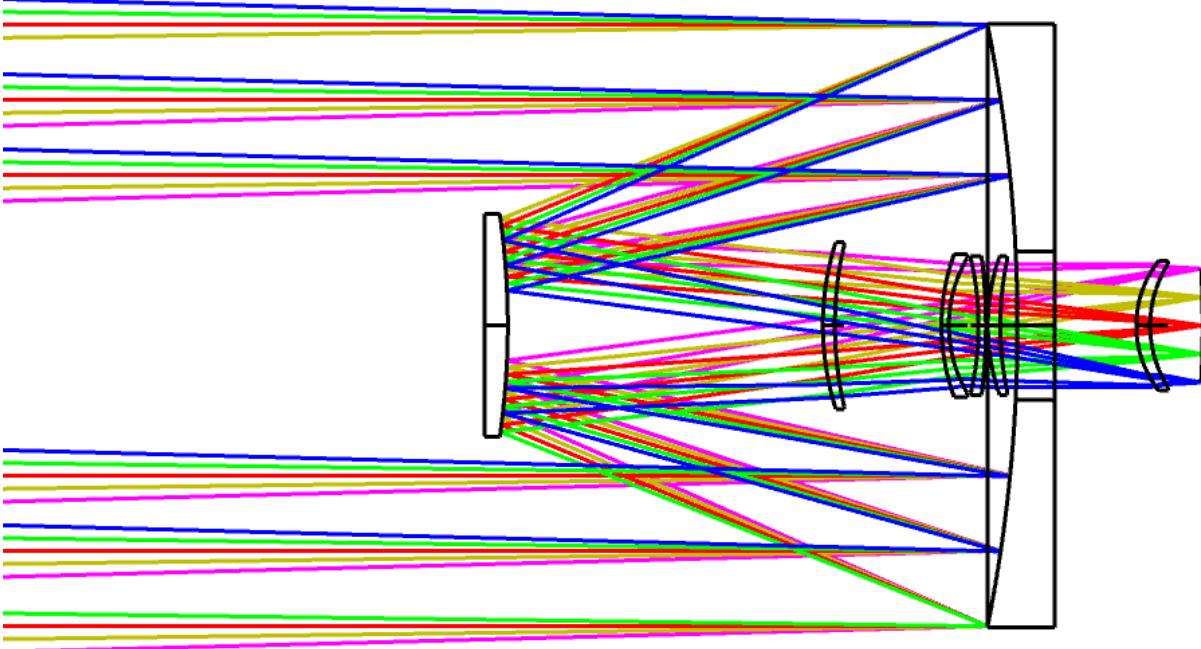


Figure 4: The optical systems on the revised wide-field Magellan telescope to be used for the MegaMapper survey. Design studies are underway on the corrector elements indicating that there are numerous vendors ready and capable of manufacturing each element of the system. This deceptively simple diagram represents the largest objective technical risk, now largely retired since the publication of Astro2020 (Smee, private communication).

Focal Plane: The focal plane is physically large and accommodates 26,100 zonal fiber positioners with a center-to-center pitch of 6.1 mm.

Each individual fiber positioner is composed of two precision, mechanical gearmotors. Such a “theta-phi” motion is the basis of both the DESI and SDSS-V positioner designs. These have the benefit of fast positioning time, high accuracy, and maintaining optical telecentricity. DESI and SDSS-V have both completed their focal planes (of 5000 single-fiber positioners, and 1000 tri-fiber positioners respectively), demonstrating that such a system can be mass produced, reliably controlled, positioned to an accuracy of 2 micron, and reconfigured in a time envelope of less than one minute.

MegaMapper represents an evolution of these focal planes with smaller positioners and

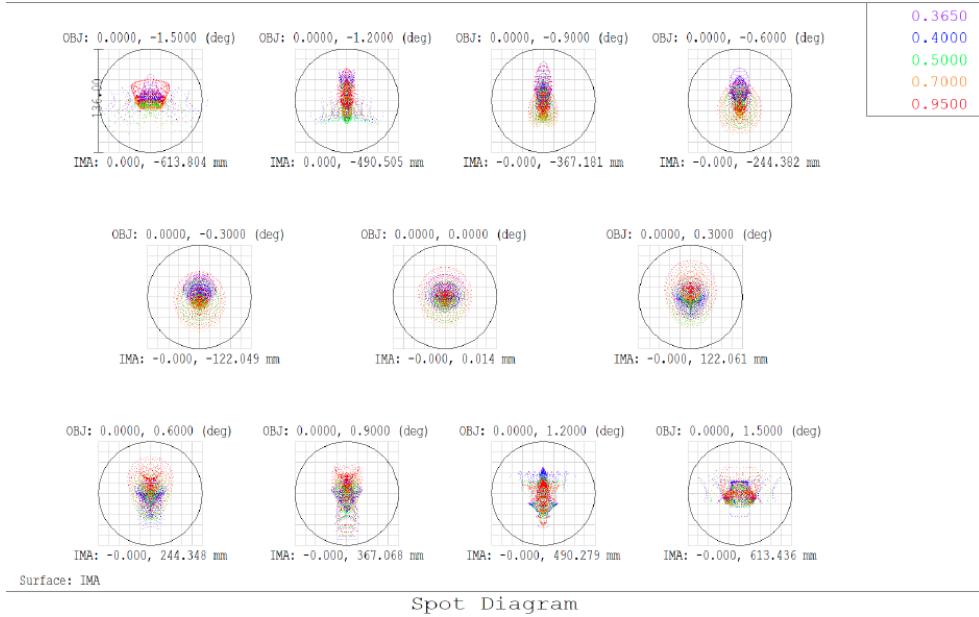


Figure 5: Spot diagram for the telescope and corrector optics. This demonstrates the excellent image quality achieved under the current optical design. (courtesy S. Smee, R. Barkhauser)

other design modifications based upon our experiences building the DESI and SDSS-V focal planes to facilitate mass production, integration, testing, and servicing. Several designs have been prototyped for positioners with a center-to-center spacing of 6.2 mm, with the second generation of the Trillium positioners shown in Figure 6. The focal plane will be divided into 348 identical 75-fiber rafts as shown in Figure 7, with 8 or 9 rafts feeding each spectrograph. Each of these 75-fiber raft modules should be a complete working miniature instrument, including robotics, fibers, support structure, and electronics. Installation and servicing of these raft modules will not require the heavy support equipment and critical lifts required for the installation of the much larger DESI focal plane petals.

Spectrographs: The spectrographs would be identical to those successfully built and tested for DESI and SDSS-V. These spectrographs went through extensive design and trade studies, and are optimized to measure redshifts of faint targets in the sky-noise limit. The performance of these spectrographs has been shown to exceed their design goals in delivered optical quality and throughput. We would choose to somewhat increase the number of fibers feeding each spectrograph from 500 to 600 or 675 by decreasing the fiber spacing at the spectrograph slit. This is supported by the as-delivered spot quality in the as-built spectrographs.

Each spectrograph is fed by a pseudo-slit with 600-675 fibers, with dichroics dividing

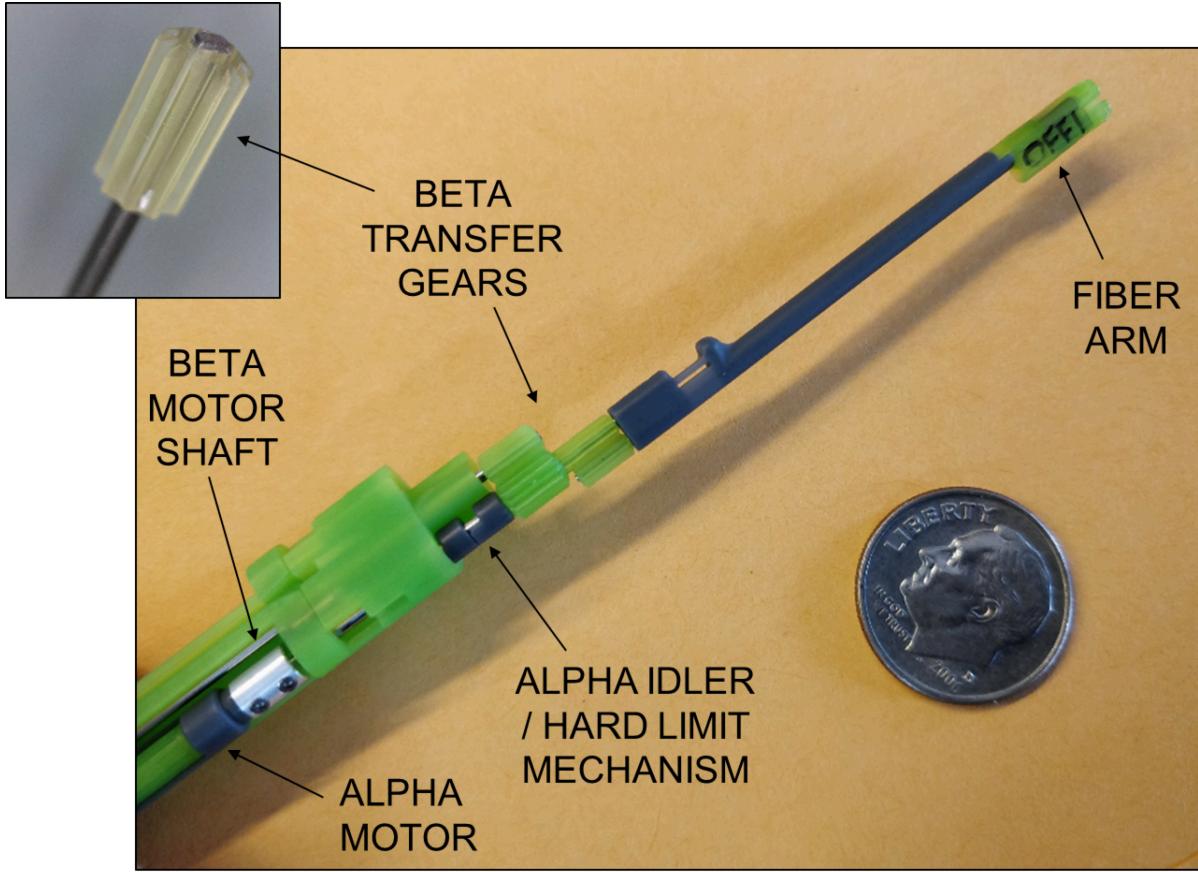


Figure 6: Prototype Trillium Mark II fiber positioner under development for MegaMapper, capable of fast re-configuration of fibers to micron-scale accuracy (courtesy J. Silber).

collimated light into three cameras. Each camera has gratings, optics and CCDs that are optimized for its wavelength range in 360–555, 555–656, and 656–980 nm channels. The spectral resolution runs from 2000 on the blue end (at 360 nm) increasing to a resolution of 5500 on the red end (at 980 nm) in order to work between bright sky lines. The as-built efficiencies are 70–90% across the full optical range.

Data System: The MegaMapper data systems will be a continuation of the data system as developed within the SDSS+DESI family of projects and operated on the NERSC high-performance computing platform. The DESI data reduction from the raw pixel level to fully-calibrated spectra and redshift-fitting is state-of-the-art today, and will be maintained and updated at least through the DESI key project from 2021-2026. Poisson-limited spectra for faint targets is achieved through a combination of stability of the spectrographs, stability of the PSF with theta-phi positioners, and a rigorous forward-modeling of the spectral extraction and sky-subtraction [32].

3 Conclusions

The MegaMapper is designed to be a high-reward, low-risk, cost-effective approach to achieving a Stage-5 Spectroscopic experiment and achieving survey speed $15\times$ faster than the current best-in-class Dark Energy Spectroscopic Instrument (DESI). The 6.5-m primary mirror has $3\times$ the collecting area of DESI, yet is no more challenging in the optical design for the focal plane and the spectrographs. Our approach is to harness the power of efficient mid-scale facility construction (i.e., the Magellan telescopes) and survey design and operation (i.e., the SDSS/DESI surveys). In combination with LSST, CMB-S4, and other cosmological probes, MegaMapper promises to explore the full range of cosmological and fundamental physics that remains essential to our understanding of the universe.

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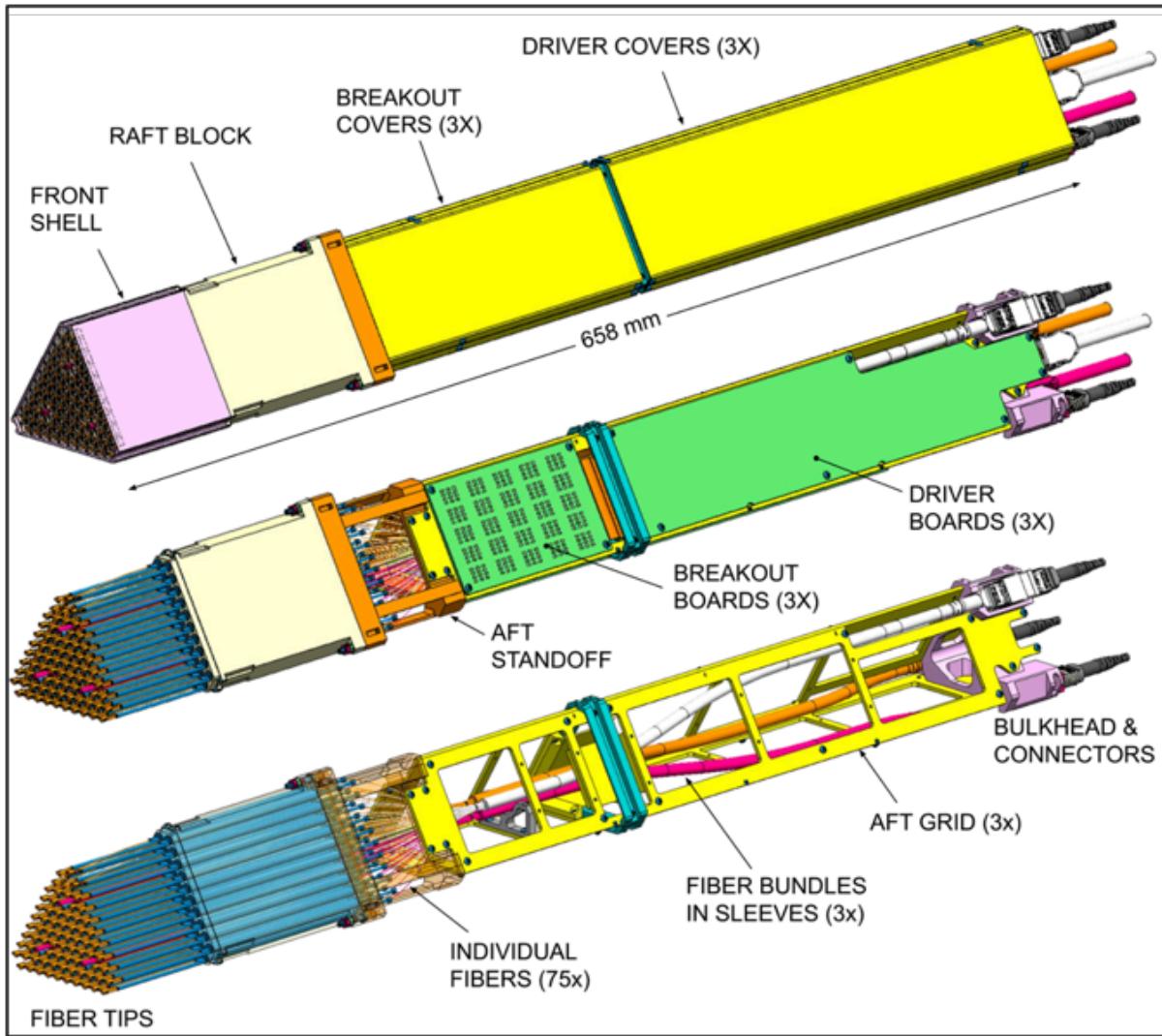


Figure 7: Mechanical drawing of a 75-fiber robot raft, where the MegaMapper focal plane would consist of 348 of these rafts. Internally, the raft is further subdivided into 3 logical and mechanical groups of 25 fibers (courtesy J. Silber).

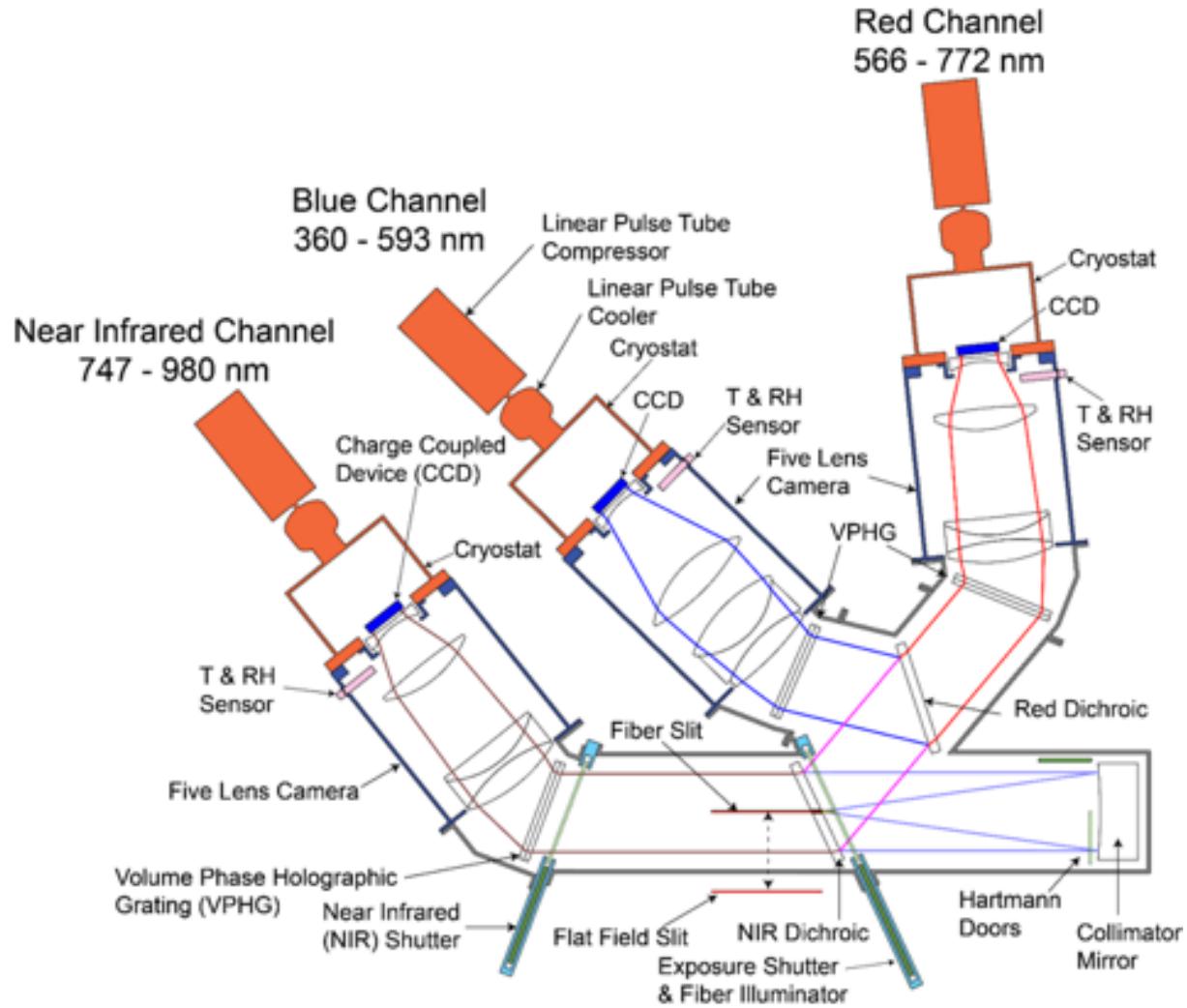


Figure 8: Optical model of the DESI and SDSS-V spectrographs, which are identical systems aside from the CCD packages. As-built efficiencies are 70–90% across the full optical spectrum.