A Concept for Seeing-Limited Near-IR Spectroscopy on the Giant Magellan Telescope

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Because staged construction of GMT will not feature AO at First Light, a simple NIR spectroscopic capability is sought to address key early science objectives including Epoch of Reionization studies.

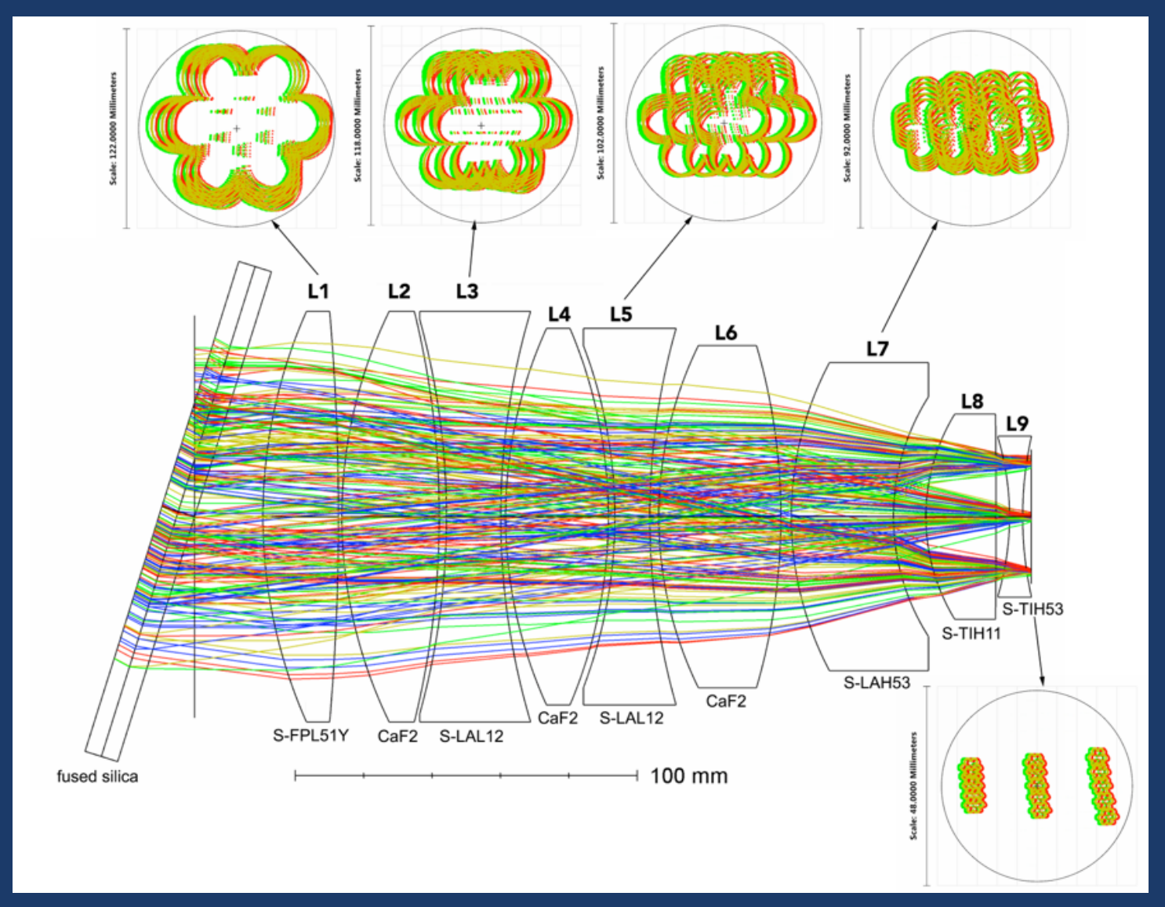
	Requirement	Goal	Driver	Affected design element	SuperFIRE
Slit width	0.7”	0.7"	LCO natural seeing/ throughput	Beam diameter	✔ (0.7”)
Slit length	7”	12-15”	Faint object sky subtraction, concurrent	X-disperser	✔ (8”)
Pixel pitch	~0.10”	0.12-0.15”	Sky-limited noise performance	Camera F/#	(✔) (0.12, 0.1, 0.1)
Spectral resolution	4500	6000	OH-free spectral path length	Beam diameter	✔ (6000)
Wavelength coverage	0.90-2.5 microns simultaneous	0.85-2.5 microns simultaneous	Lya @ z = 6-9 CIV @ z = 5-9	Optics, coatings	✔ (0.87-2.45)
Diffraction grating	Existing ruling	Existing ruling	Cost/schedule	Grating choice	✔
Detectors	Existing model	H2RG	Cost/schedule	Sensor, Grating choice	✔
Low-resolution mode	none	R~1000, longslit (1’) JHK	Throughput, transits, transients (LSST/LIGO),	Grating mechanism	✔ (R=800, 15”)
Volume envelope	Within folded port standard envelope	<1.5x larger than FIRE, or about 1m track	Dewar size, complexity, port availability	Beam diameter	✔

Many top-level scientific objectives for the Giant Magellan Telescope (GMT) require near-infrared (NIR) spectroscopy, but this capability has not been designed into the early operations architecture of the observatory. GMT’s initial instrument suite consists of a seeing-limited multi-object optical spectrometer (GMACS) and a high-resolution fiber-fed optical spectrometer suitable for precision radial velocity measurements (G-CLEF). Still, background-limited IR spectroscopy is a compelling application for Extremely Large Telescopes (ELTs) even in the seeing limit. This is in part driven by the early science these telescopes are expected pursue regarding the early universe, but also because read noise limits the performance of IR spectrometers on existing telescopes (i.e. $D = 6 - 10$ meters) with sufficient spectral resolution to split the OH-line foreground of the night sky. Even the James Webb Space Telescope (JWST) falls into this class—since JWST/NIRSPEC employs identical CMOS sensors on a 6.5 meter effective aperture, it will also be read-noise limited at wavelengths where thermal emissivity does not dominate.

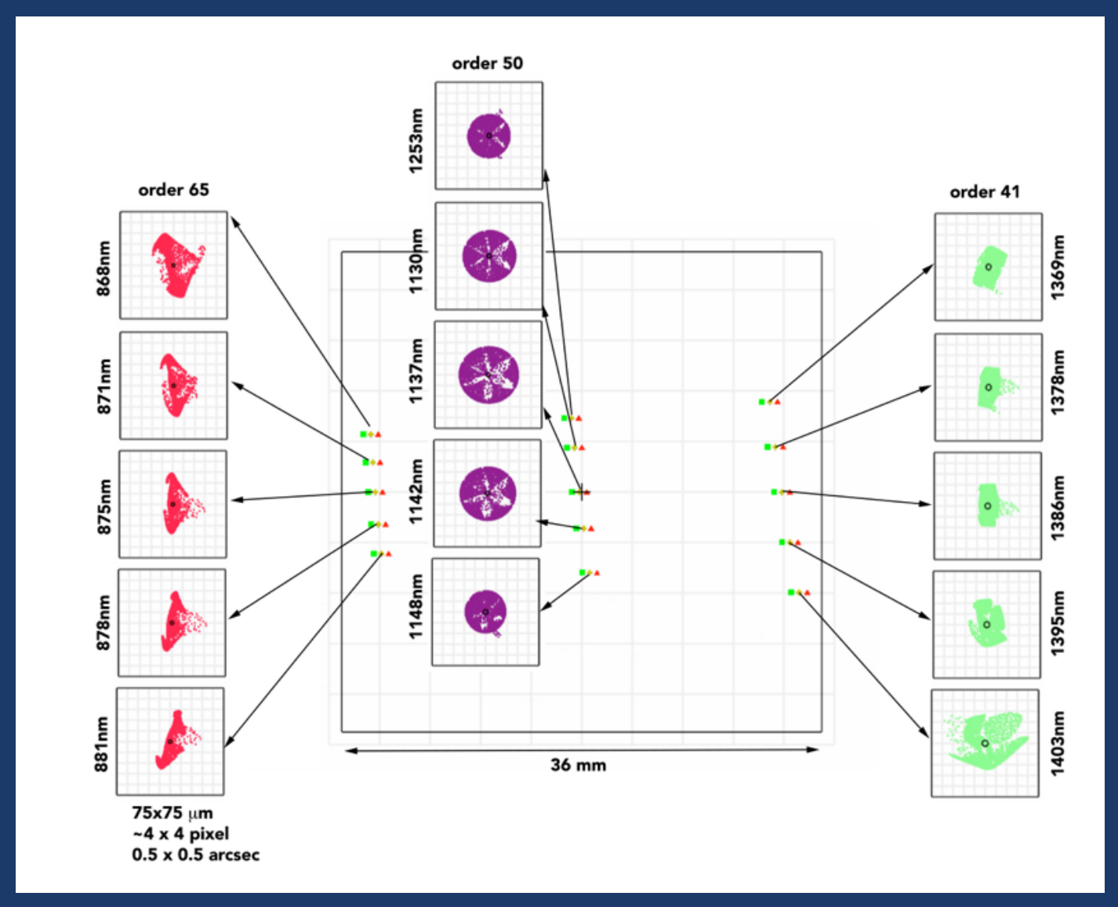
In time the demand for IR spectroscopy on GMT will be addressed by a followup generation of Adaptive Optics (AO) instruments, which includes an $R = 50,000$ spectrometer operating at $\lambda = 1.12 - 5.0\mu m$ for bright targets (GMTNIRS) and an $R = 5000$ NIR fiber-fed integral field spectrometer with spatial sampling of 0.008” (min) to 0.05” (max) in a single NIR band (GMTIFS). Early operation plans feature a staged commissioning sequence in which the telescope will initially be operated in the seeing limit during installation of the mount and primary mirror segments. The AO system will then be commissioned in a subsequent phase as the enclosure and mount are completed and the primary mirror is properly phased.

Because GMT’s baseline NIR spectrometers all require a fully-operational AO system, there is the potential for the AO commissioning schedule to drive the timescale on which GMT can pursue key science involving the high redshift universe, low mass stars, dust-obscured environments and broadband transients. We were tasked to explore options for seeing-limited NIR spectroscopy at GMT, to better position the observatory to capitalize on these science opportunities during early commissioning.

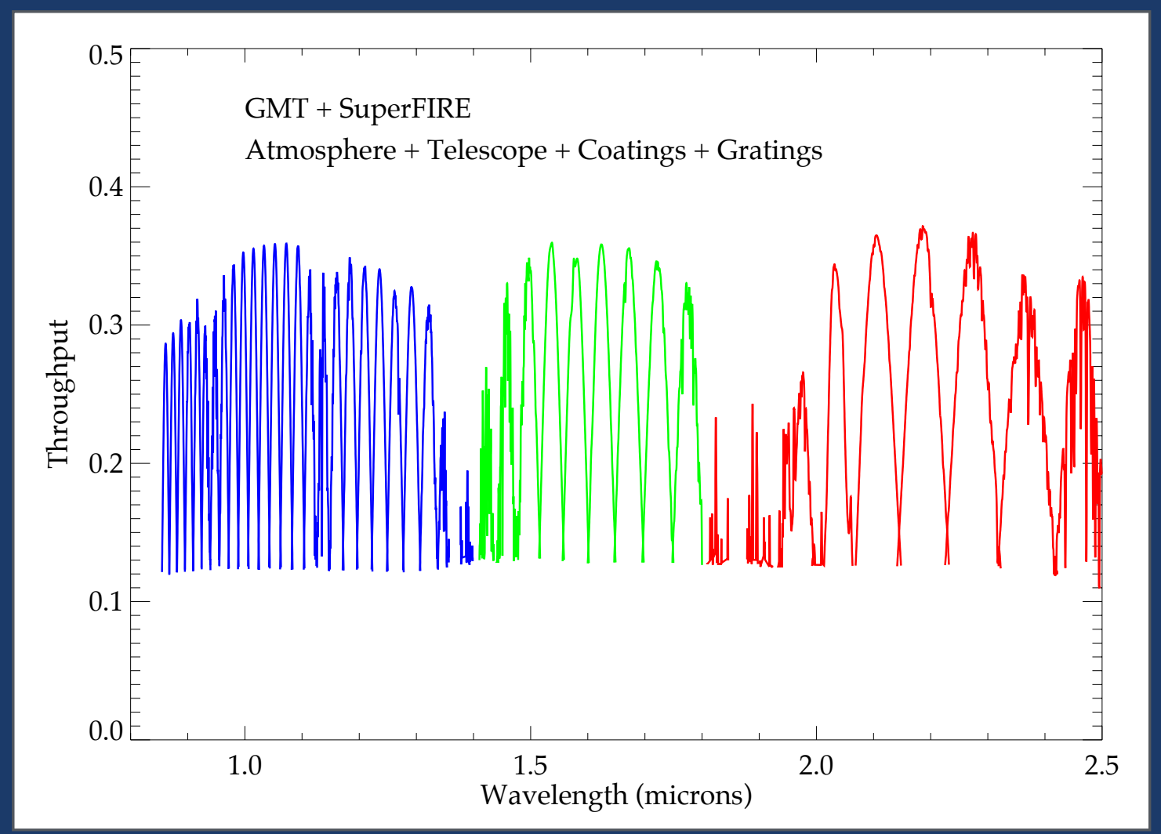
F/1.0 - F/1.2 cameras are required to achieve an appropriate seeing-limited pixel scale. This is the most challenging design element. We display below a proof-of-concept all-spherical model for the fastest camera that meets requirements and can be improved in the future via use of aspheres.



Preliminary layout of the F/1.0 yJ band spectrograph camera. This is a 9-element, all spherical, airspaced design to minimize CTE-induced stresses from bonded elements in the cryostat. The entrance pupil, located near the VPH grating (which is shown at left), is 120 mm in diameter. Footprint diagrams are shown for several representative lenses in the optical train; the small overlapping footprint for all field angle/wavelength combinations reveals the motivation for using a white pupil configuration. This layout is only a conceptual design and will be further optimized through better glass selection and use of aspheres.

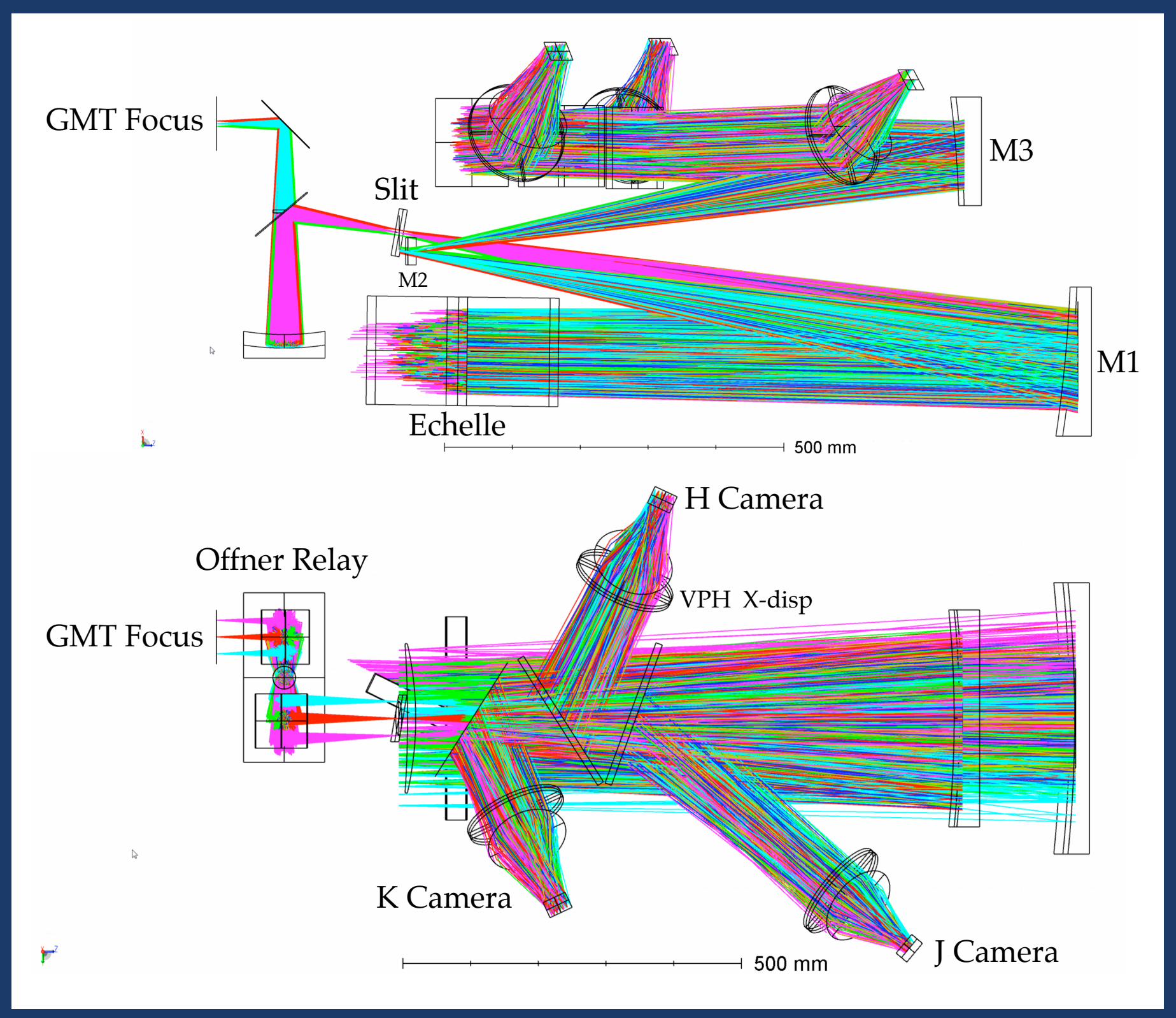


Focal plane footprint diagram for the yJ band camera along with inset spot diagrams indicating performance along different portions of the echelle trace. Here, the inset boxes are 0.5″ or 4 pixels per side. The 90% encircled energy diameter is 0.2″ for all combinations except the reddest wavelength, or roughly 30% of the median seeing. Further optimization of the camera through use of aspheres should improve these preliminary results, which are intended only as a proof-of-concept.

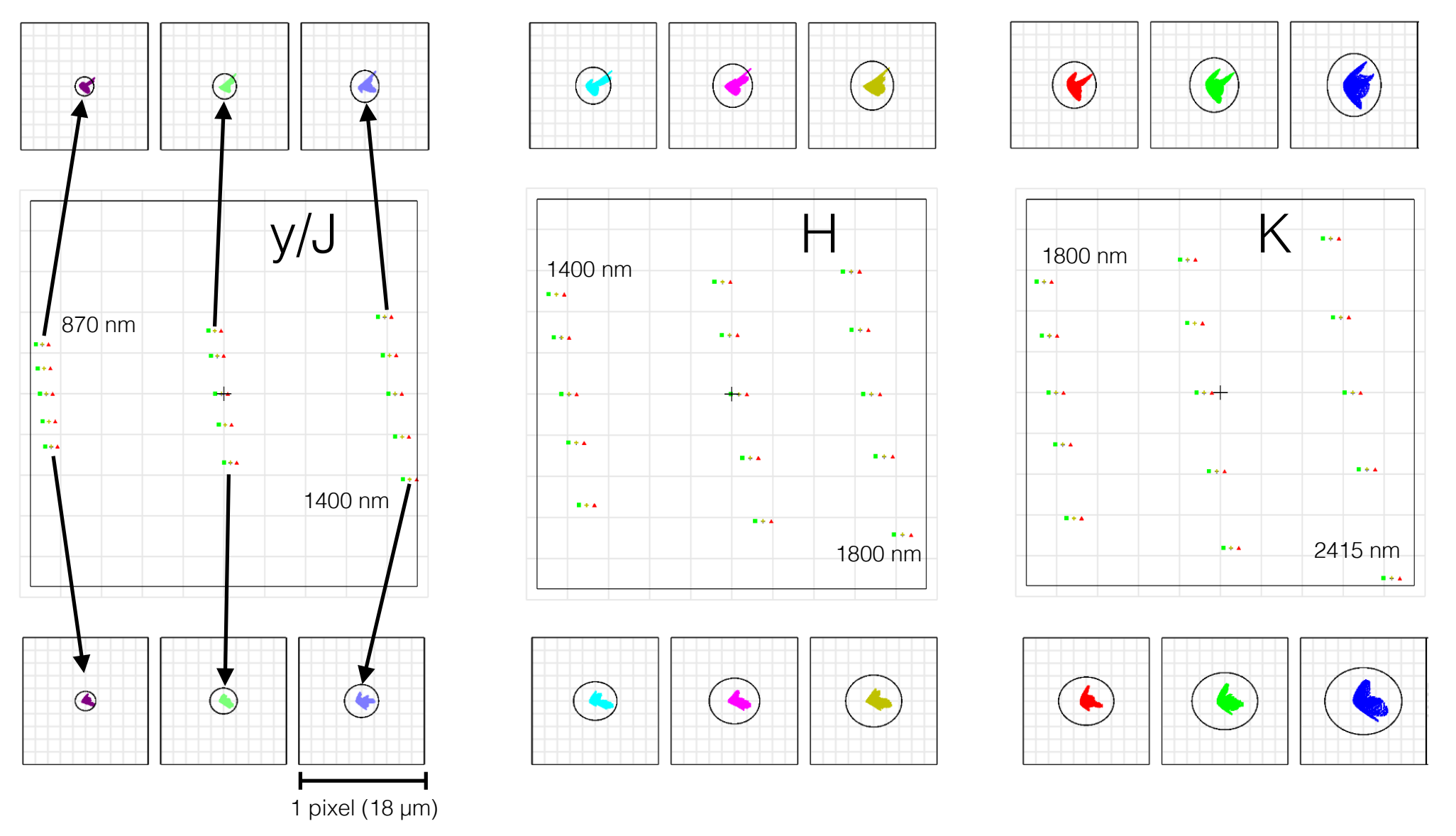


Projected throughput of SuperFIRE, including losses from the Earth’s atmosphere, telescope, and instrument. The instrument contribution consists of optical surface losses, blaze functions of the echelle grating and VPH cross dispersers (modeled analytically using the Kogelnik approximation), and the H2RG sensor’s quantum efficiency. No slit losses are included. This throughput is similar to Magellan/FIRE at similar plate scale, so GMT’s aperture should deliver large improvements in system sensitivity. This is particularly true in yJ and portions of H, where FIRE is read-noise limited on Magellan.

Building on MIT’s experience with Magellan/FIRE, we have developed a new design that delivers identical spectral resolution and pixel scale for GMT’s 4x larger aperture.



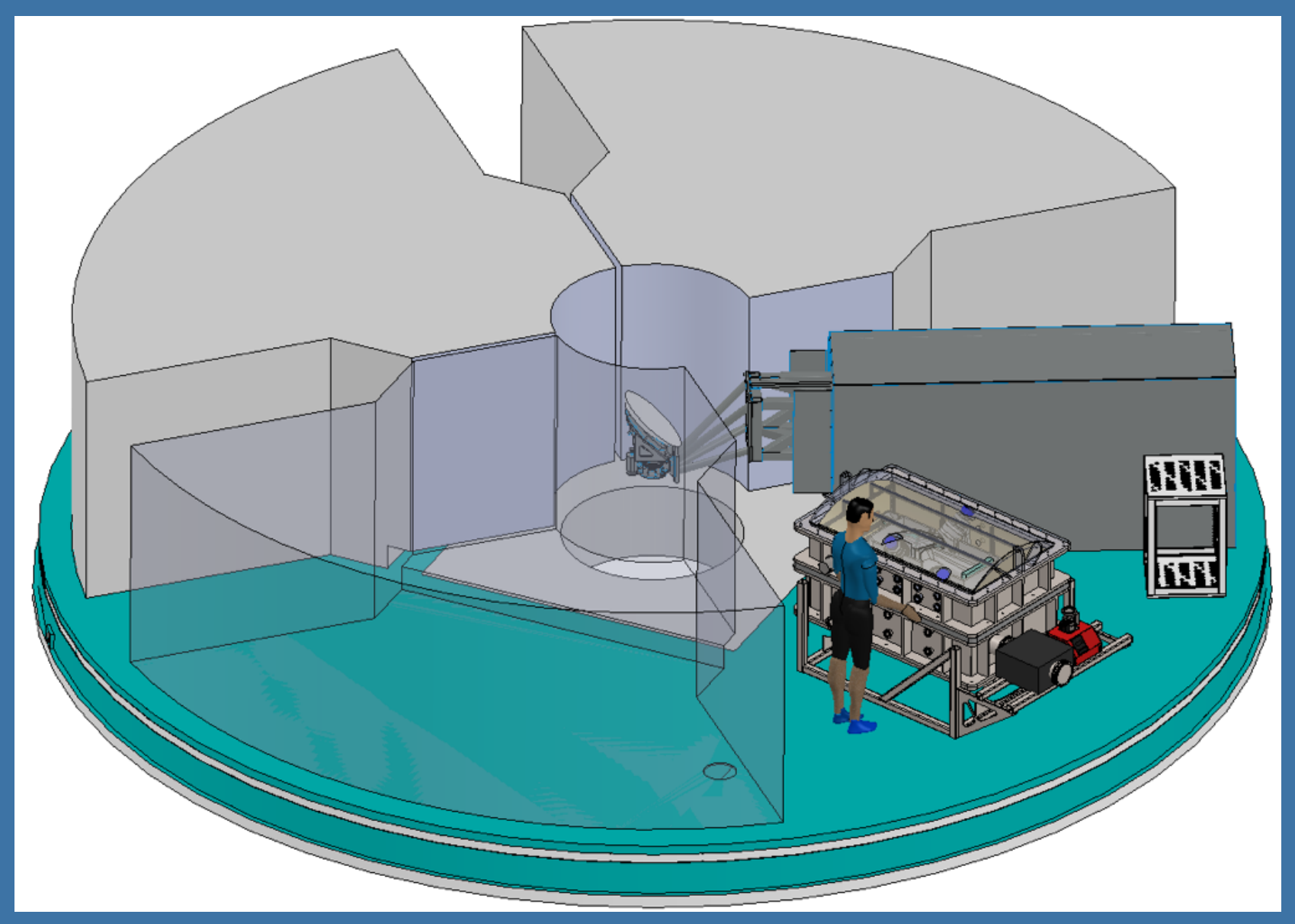
Basic layout of SuperFIRE as seen from the side (top panel) and above (bottom panel), with scale bars for reference. A cold Offner relay baffles thermal light from the telescope before the slit. The, after transmission through the slit, a collimated 132mm diameter beam is projected into the echelle and returned off M1. An intermediate focus with all orders overlapping is formed at M2, which is figured as a toroidal Mangin mirror to correct Petzval curvature. After reflection from the pupil transfer mirror (M3), the beam is split into three arms by dichroic filters. Each arm has a dedicated VPH cross-disperser, camera, and H2RG sensor. In this view, paraxial cameras are shown for simplicity.



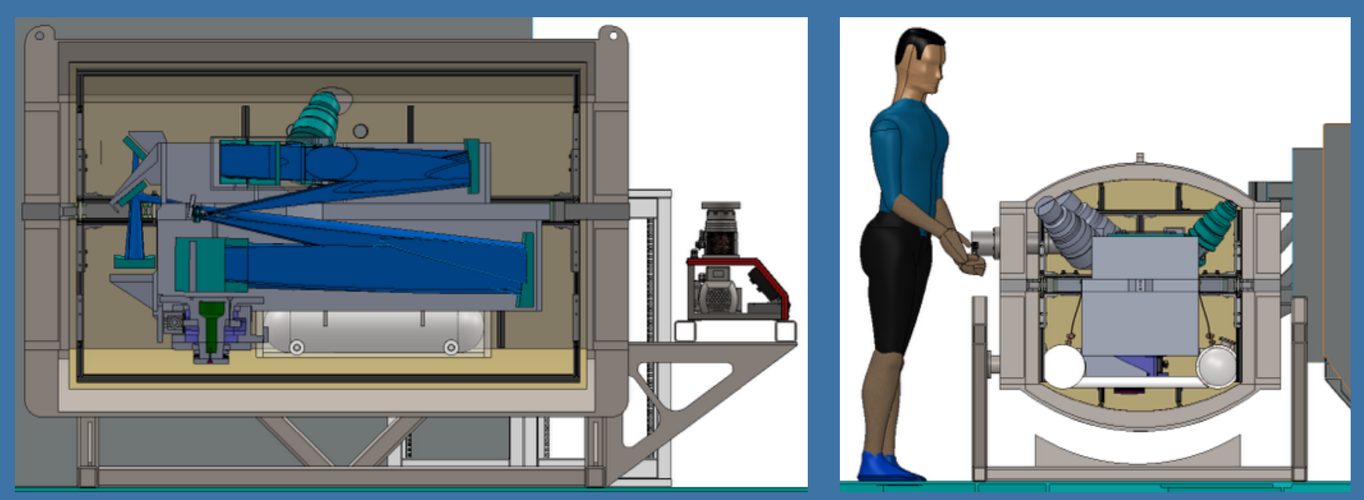
Footprint diagrams at the focal plane sensor for the three cameras. In each panel, we show five wavelengths across the free spectral range (top to bottom) for the bluest, central, and reddest orders from left to right, with wavelengths labeled. For each configuration of order number and wavelength, three field angles are shown corresponding to the center of the slit, and ±4″, i.e. the slit edges. Inset in each diagram are 1×1 pixel boxes (0.122″ square) indicating the image quality of the spectrograph with paraxial cameras (i.e. isolating aberrations from the spectrograph optics). The circles in these spot diagrams denote the diffraction limit, indicating that aberrations for the total system are dominated by the cameras.

A white-pupil design with 120mm beam keeps the layout compact. The spectral resolution is sufficient to minimize contamination from foreground terrestrial OH emission, and a large pixel scale leverages GMT’s aperture to overcome the read noise floor that limits IR spectrometers both on 6-10 meter telescopes, and on JWST.

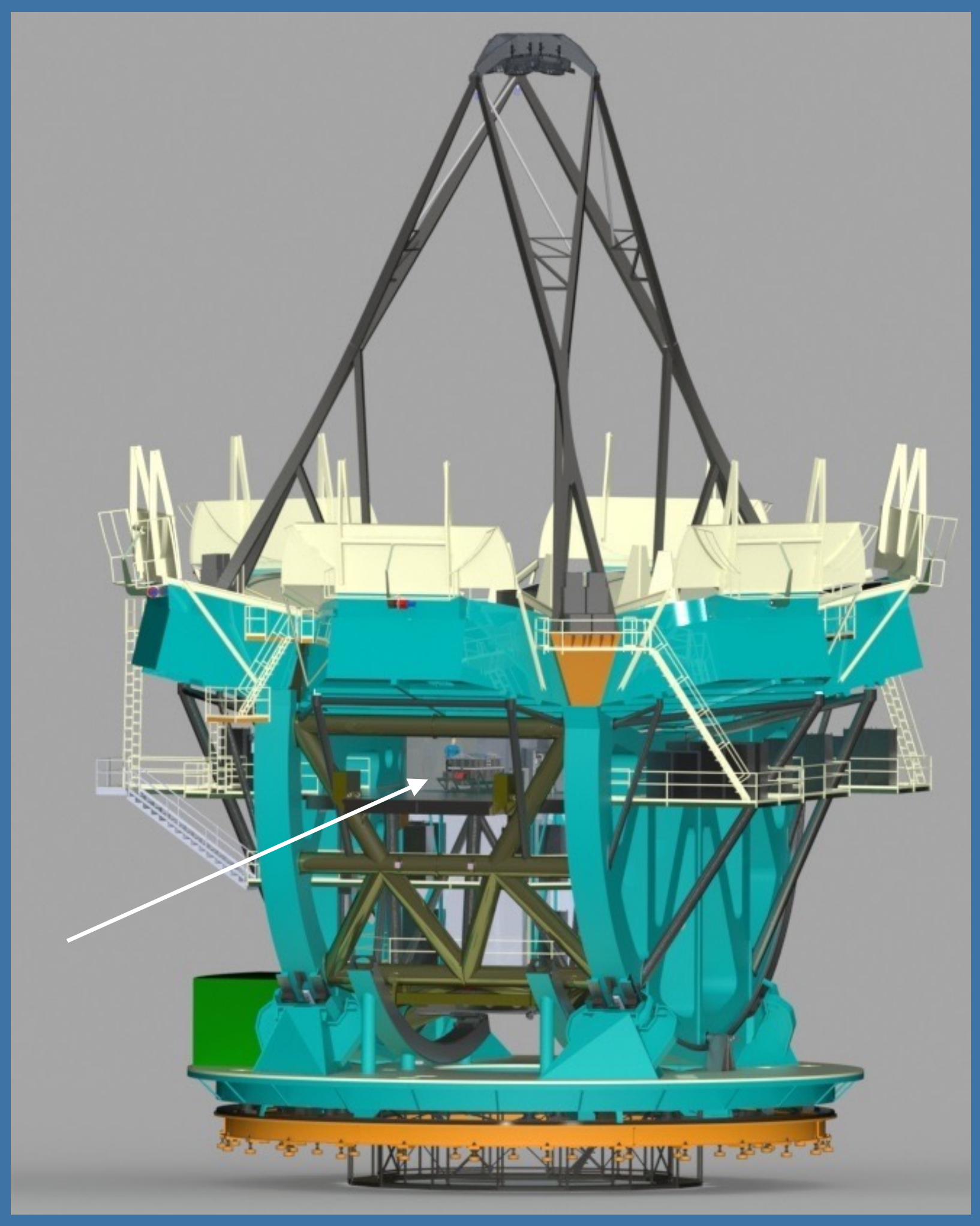
The design is extremely compact for an ELT scale instrument (1.8m x 1.5m x 1.2m) and easily meets GMT mass and volume requirements. It incorporates just two mechanisms and all-COTS detectors, gratings, and components with existing astronomy heritage.



Mechanical model of SuperFIRE on the Instrument Platform. The transparent solid shows a representative volume envelope for instruments at this port, illustrating that SuperFIRE easily meets these requirements. At 1350 kg, it also meets the GMT requirement of <7000 kg with margin.



Close-up of the dewar volume, with left panel (cut-away, closer view) illustrating the packaging of beams inside the vacuum enclosure. This model was developed to verify the volume envelope of the dewar and estimate thermal loads for sizing of the cooling system. Two large LN2 reservoirs (shown at bottom) provide and estimated 48 hours of hold time in a cold configuration, while avoiding technical vibrations associated with cryocoolers that could interfere with AO commissioning.



Rendering of SuperFIRE mounted on the rotating Instrument Platform of GMT, under the primary mirror. The spectrograph would be addressed by a dichroic diagonal tertiary that transmits optical light to a seeing-limited optical spectrometer (GMACS) below the platform. This would permit simultaneous UV to NIR spectroscopy with GMT in a similar configuration to X-Shooter on the VLT, as an early commissioning science configuration for GMT.

This design study demonstrates the feasibility of developing relatively aforable spectrometers at the ELT scale, in response to the pressures of joint funding for these telescopes and their associated instrument suites.

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