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Mauna Kea Spectrographic Explorer (MSE): New Preliminary Design for the Multi-object High Resolution Spectrograph

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ABSTRACT

The Maunakea Spectroscopic Explorer (MSE) project will transform the CFHT 3.6m optical telescope to an 11.25 m multi-object spectroscopic facility with an ability to simultaneously detect thousands of objects with three spectral resolution modes, low resolution of R ~ 3,000, moderate resolution of R ~ 5,000, and high resolution of R 20,000 ~ 40,000, respectively. The multi-object high resolution (HR) spectrographs can derive simultaneously around one thousand high-resolution spectra of Blue, Green, and Red channels, respectively. Based on the discussion of the science cases in 2019, the design team suggested that the optimal design of HR spectrograph should balance between the new scientific requirements and technical feasibility. Here, the HR design team shows the trade-off study's progress and introduces a new preliminary design.

Keywords: Maunakea Spectroscopic Explorer, Multi-object Spectrograph, High Spectral Resolution

1. INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE) project will transform the CFHT 3.6 m optical telescope to an 11.25 m multi-object spectroscopic facility. It will have the capabilities to observe objects with a range of spectral resolutions, from R ~ 3,000 to R ~ 40,000, and all the spectral resolutions can be available at the same times and across the entire field[1]. As a dedicated survey facility, MSE is designed to execute a wide variety of scientific programs simultaneously and

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Ground-based and Airborne Instrumentation for Astronomy VIII, edited by Christopher J. Evans, Julia J. Bryant, Kentaro Motohara, Proc. of SPIE Vol. 11447, 114478B · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2561553

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efficiently. This transformative project successfully attracts more international partners from Australia, Canada, China, France, India, South Korea, the United Kingdom, and the United States of America. The latest project progress will be reported by Sezto[2] at this conference.

The MSE will be a state-of-the-art observatory because it benefits from the latest technological advancements made by other top astronomical facilities worldwide, *e.g.,*WEAVE at WHT[3], HERMES at AAT[4], 4MOST at VISTA[5], and PFS at Subaru[6]. For the diverse spectroscopic observations, the MSE will employ a suite of multi-object low/medium-resolution spectrographs (LMR) to provide the spectral resolution from R~3,000 to R~7,000 with a the full wavelength range from 360 nm to 1,800 nm, and another suit of high-resolution spectrographs (HR) to provide a spectra with a resolution of R ~ 40,000 at the visible band from 360 nm to 900 nm. The LMR spectrographs suite will accommodate 3249 fibers, and the HR spectrographs suite will accommodate another 1083 fibers[7].

With the high-resolution spectroscopy, MSE allows us to detect the interesting weak spectral lines of faint objects, which is essential to probe various chemical species, and to provide key insights into the evolution of the Galaxy and the formation of the chemical elements. The ESA space satellite *Gaia* is dedicated to probing the proper motion and parallax of all stars brighter than G = 20 magnitudes. MSE will be the ultimate *Gaia* follow-up facility, in particular, which decomposes the outer regions of the Galaxy into its constituent star formation events by accessing a range of chemical tracers that sample a large number of nucleosynthetic pathways. *PLATO* is another ESA mission developed to monitor a large number of bright stars to search for planets. MSE will provide spectroscopic characterization with high resolution and high signal-to-noise ratio (SNR) at the faint end of the *PLATO* target distribution (g ~ 16) to allow for statistical analysis of the properties of planet-hosting stars as a function of stellar and chemical parameters[8].

In 2018, the MSE Project Office (PO) summerized the technical and programmatic progress at the Conceptual Design (CoD) phase. To explore a better technical solution, PO is currently under a preparation phase to the Preliminary Design Phase (PDPRR) from 2018 to 2020. At this conference, the Centre de Recherche Astrophysique de Lyon (CRAL) of France will update the instrument design for the LMR Spectrographs in the paper, "*Maunakea Spectroscopic Explorer Low Moderate Resolution Spectrograph: paths toward the Preliminary Design Phase*"[9]. The Nanjing Institute of Astronomical Optics and Technologies (NIAOT) of the Chinese Academy of Sciences will introduce the HR spectrographs' design progress here.

This paper is organized as follows: Section 2 reviews the design history for the HR spectrographs. Section 3 describes the new design.

2. DESIGN EXPLORATION

2.1 Spectral Resolution

Benefitting from the success of large sky surveys, such as SDSS[10], 2df[11], and LAMOST[12], technologies on multi-object fiber-fed spectrographs (MOS) had further developed in the past years. The next generation of the MOS spectrographs aims at the spectral survey with a high resolution of $R \geq 20{,}000$ besides the regular low and medium ones. Table 1 shows some advanced instruments developed for the medium and large telescopes in recent years. Equation 1 shows that the dispersion power (A) is proportional to the product with parameters among telescope and spectrograph ($Dt \times R \times \Phi$). It indicates that MSE-HR will provide the most challenging dispersion power (A) by comparing the fourth column values ($Dt \times R \times \Phi$). It leads that the spectrograph faces a tough nut to crack with the collimated aperture and the dispersers.

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$$A = D_t \times R \times \Phi / \lambda \qquad (1)$$

(Dt denotes telescope aperture, R denotes the spectral resolution, Φ denotes slit width on sky, and λ denotes the wavelength.)

In 2015, the NIAOT held the first MSE engineering workshop in Nanjing, and then began a discussion to design for the High-Resolution (HR) spectrographs at the second engineering workshop in Paris. The design group has explored different optical systems for this transformative instrument since 2016 (Figure 1). This long trade-off study is worth reviewing to summarize some experience for the next design phase.

Table 1. Some multi-object fiber-fed spectrographs developed in recent years.

Instrument	Telescope (a) D_t	(b) $R \times \Phi$	$D_t \times R \times \Phi$ (a) × (b)	Multiplexing num.	# of spec.	Dispersers
MSE-HR[8]	MSE [11.25m]	Max. 32,000"	360,000	1084 fibers (0.8")	2	TBD
MOONS[13]	VLT [8.2m]	Max. 18,000"	147,600	1000 fibers (1")	1	LR: VPH grating HR: VPH grism
PFS[6]	Subaru [8.2m]	Max. 5,500"	45,100	2400 fibers (1.1")	4	VPH grating
Hetochelle[14]	MMT [6.5m]	Max. 57,000"	370,500	240 fibers (1")	1	Echelle grating
WEAVE[3]	WHT [4.2m]	Max. 26,000"	109,200	960 fibers (1.3")	1	VPH grating
LMRS[15]	LAMOST [4m]	LR: 3,300" MR: 16,500"	LR: 13,200 MR: 66,000	4000 fibers (3.3")	16	VPH grating
4MOST[5]	VISTA [4m]	Max. 27,000"	108,000	LR: 1624 fibers HR: 812 fibers	2	VPH grating
HERMES[4]	AAT [3.9m]	Max. 47,000"	183,300	392 fibers (1.7")	1	VPH grating

* The MSE-HR specification is given in the 2018 paper, which is different from the corresponding content in this paper.

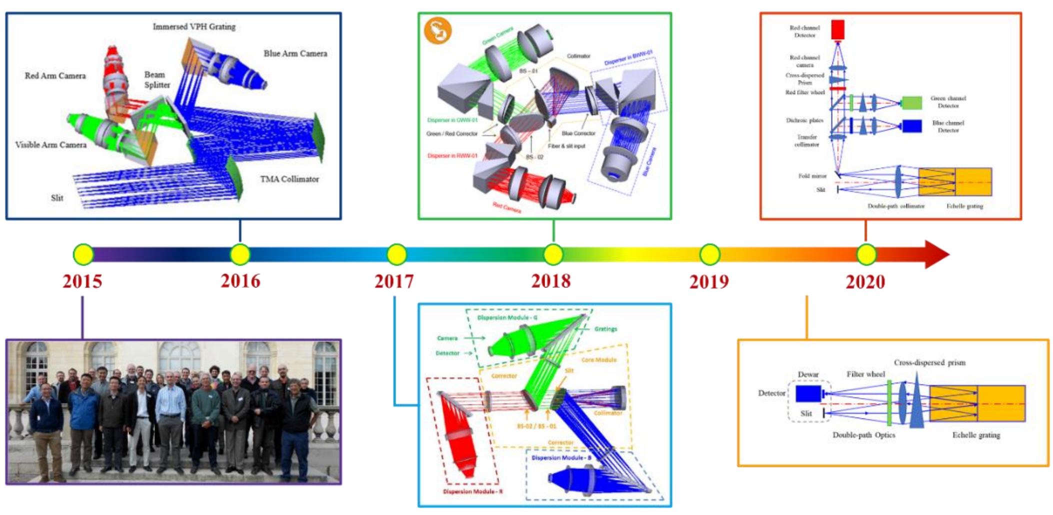

Figure 1. Milestones during the MSE-HR design period

The first optical design proposed in 2016 [16] was inspired by a transmission image slicer design that integrates fibers one by one along the slit. The image slicer is composed of two pairs of prisms. The former part can separate the image along the slit, and the latter part eliminates the spacing between two slices. This design reduces the requirement of the product of resolution and slit width from 30,000" to 15,000". It seems feasible for the spectrograph to achieve the resolution

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performance by a reasonable-size MOS system. The design team began to explore another design in 2017 because image slicer array brought the other technical problems on the fiber unit at slit, data reduction, and fiber accommodation by a single spectrograph. During the CoD review in 2017, the design team was aware that a regular MOS design with a large collimated aperture of 300 mm in diameter, and faced serious challenge in throughput and polarization of a large VPH grating due to its blaze angle of about 68°. This problem has also been mentioned in HERMES at AAT. Another optimized design with a type of 'diamond' grisms was proposed in 2018[8], which adopted an off-axis fast collimator (F/2.05) instead of on-axis Schmidt system for higher optical throughput, and the 'diamond' grism with a ruling density of up to 6,000 l m^{-1}[17] is capable of providing unpolarized diffraction efficiency higher than 80 %. Although the design performance meets the requirement, it's costly for the vendors to develope the relevant technology for the grism fabrication. Up to this optimized design, we had tried most of the optical design with single-diffraction-order gratings or grisms. Table 2 summarizes their optical parameters and technical advantages and disadvantages. It indicates that the optical designs were always limited by the dispersion capability and inspired the design group and the SWG to collaborate and iterate closelybetween science cases and instrument specifications.

Table 2. Main parameters of different designs from 2016 to 2018

Designs	2016	2017	2018
Multiplexing	4 spec. for 1084 fibers	2 spec. for 1084 fibers	2 spec. for 1084 fibers
Fiber	Φ1"	Φ0.8"	Φ0.75"
Resolution	R_B=40K, R_G=40K, R_R=20K	R_B=40K, R_G=40K, R_R=20K	R_B=40K, R_G=40K, R_R=20K
Dispersers	'Diamond' Grisms (θb≈45°) Diffraction order = 1	VPH gratings (θb≈68°) Diffraction order = 1	'Diamond' Grisms (θb≈53°) Diffraction order = 1
Collimated Aperture	Dc = 250mm F/20 (TMA optics)	Dc = 300mm F/3.5 (on-axis Schmidt optics)	Dc = 300mm F/2.05 (Off-axis houghton optics)
Detector	9K × 9K pixels @ 10 μm	6K × 6K pixels @ 15 μm	6K × 6K pixels @ 15 μm
Advantage	Lower requirement of dispersers and aperture	Compact and regular optics	High throughput and image quality
Disadvantage	Complexity due to slice spectrums, double spectrographs	Low throughput and serious polarization of gratings, Large optics	Technical development of high-ruling-density grisms, Large optics

Table 3. Change of design requirement in the past three years

Year	Multiplexing (fibers)	Spectral Arms	Resolution	Window Bandpass	Instrument Sensitivity (1hr)
2017	1084 fibers (Φ0.7"-0.8")	B: 360 nm - 450 nm G: 450 nm - 610 nm R: 610 nm - 900 nm	R_B=40K R_G=40K R_R=20K	B: 1/30 G: 1/30 R: 1/15	mag = 20 SNR=5@<400nm SNR=10@>400nm
2018		B: 360 nm - 430 nm G: 430 nm - 510 nm R: 510 nm - 900 nm			
2019	500 - 1084 fibers (Φ0.75"-0.8")	B: 360 nm - 500 nm G: 500 nm - 600 nm R: 600 nm - 700 nm	R_B=40K R_G=30K R_R=20K	B: 1/30 G: 1/22 R: 1/15	mag = 19 - 19.5 SNR=5@<400nm SNR=10@>400nm
2020		B: 360 nm - 420 nm G: 420 nm - 580 nm R: 580 nm - 820 nm	R_B=30K-40K R_G=20K-30K R_R=30K-40K	TBD	

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The SWG extensively discussed the scientific strategies and detailed requirements through the science workshop and questionnaire in 2019[18]. The PO organized communication between science case requirements and technology feasibility from 2019 to 2020. Table 3 shows the several changes of the design requirements after the CoD review. At present, it resulted in reduction of requirements in resolution, wavelength coverage, and magnitude. This compromise relieves much pressure on the optical design. On the other hand, the design group considers another way by using a medium-resolution echelle grating, such as the design applied in Hetochelle at MMT (Table 1). It will be possible to bring a new transformation for our optical design and the instrument operation.

2.2 Instrument Sensitivity

Table 3 also highlights another important design requirement on instrument sensitivity. With an exposure of 1hour, the MSE HR spectrographs are expected to observe targets of mags = 19 - 19.5 for a signal-to-noise ratio of ≥ 5 at wavelengths shorter than 400 nm and of ≥ 10 at wavelengths longer than 400 nm. Thus, the throughput requirement of the MSE-HR spectrographs can be derived from a direct simulation from the science target to the slit. Such simulation considers the astrophysical processes, the atmospheric condition at Mauna Kea, the telescope optics, and the fiber transmission system. Figure 2 shows the throughput requirement of the MSE-HR spectrograph derived from a stellar photometric system. Two series of curves are compared under the different requirements in 2018 and 2020. The required throughput* increases rapidly at two bands of short wavelengths, including 360 nm - 380 nm and 400 nm - 420 nm (Red bands in Figure 2).

From these curves in Figure 2, it's reasonable for a conventional MOS spectrograph to achieve its optical throughput higher than 35 % over the wavelength from 380 nm to 900 nm. For a large telescope such as MSE, these requirements become more challenging due to the increased optical complexity. And the dispersers play the most critical role in observing faint objects.

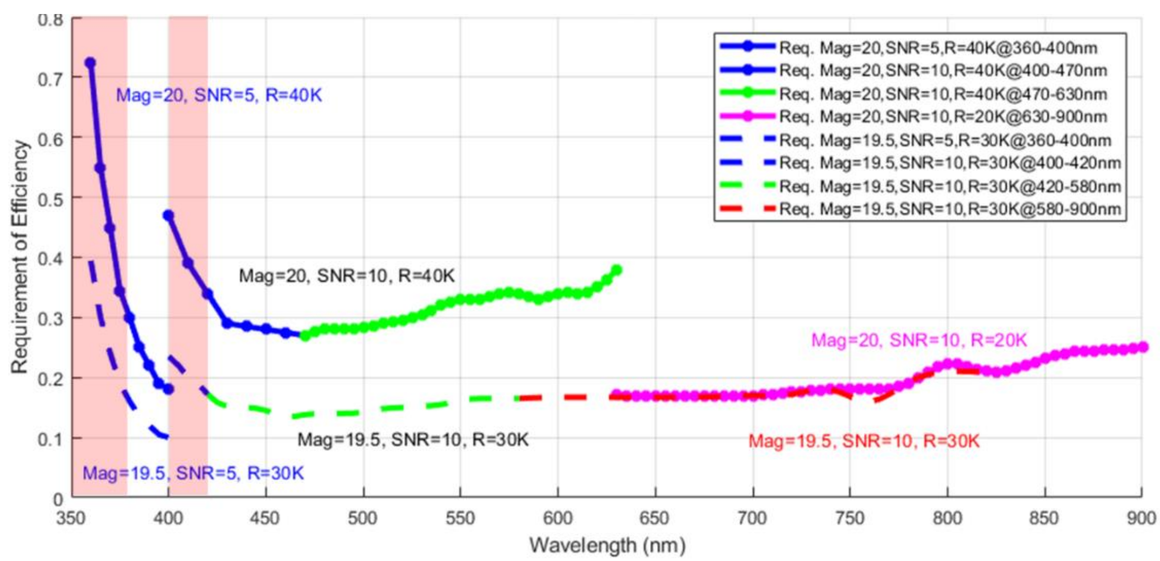

Figure 2. Throughput requirement of HR spectrograph

* The HR spectrograph throughput requirement assumes no improvements from other subsystems from the science target to the slit.

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3. NEW DESIGN

3.1 Optical Design

The original intention of using echelle grating is to have some advantages in spectral dispersion and mature technology of fabrication. Equation 2 can be used to compare the performance of the spectrographs at different aperture telescopes, and the high dispersion power (A) of echelle grating benefits from the product with high diffraction order (m) and the medium number of ruling lines (N) (Table 4). Thus the MSE-HR spectrograph requires only a large echelle grating with low ruling density (σ), within the fabrication capabilities of current techniques and grating facilities. For a high resolution of *R* = 30K, the MSE-HR spectrograph requires the dispersion power of A≥3e+6. A large-size R2.6 echelle grating with a ruling density of 52.67 l mm^{-1} requires a grating area of 240 mm × 660 mm to accommodate 34.4K lines (N) instead of 3M lines of the grism.

$$\mathrm{A} = \mathrm{m} \times \mathrm{N} = \mathrm{m} \times \sigma \times \mathrm{S} = D_t \times R \times \Phi/\lambda \tag{2}$$

(σ denotes the ruling density, S denotes the ruling area of grating.)

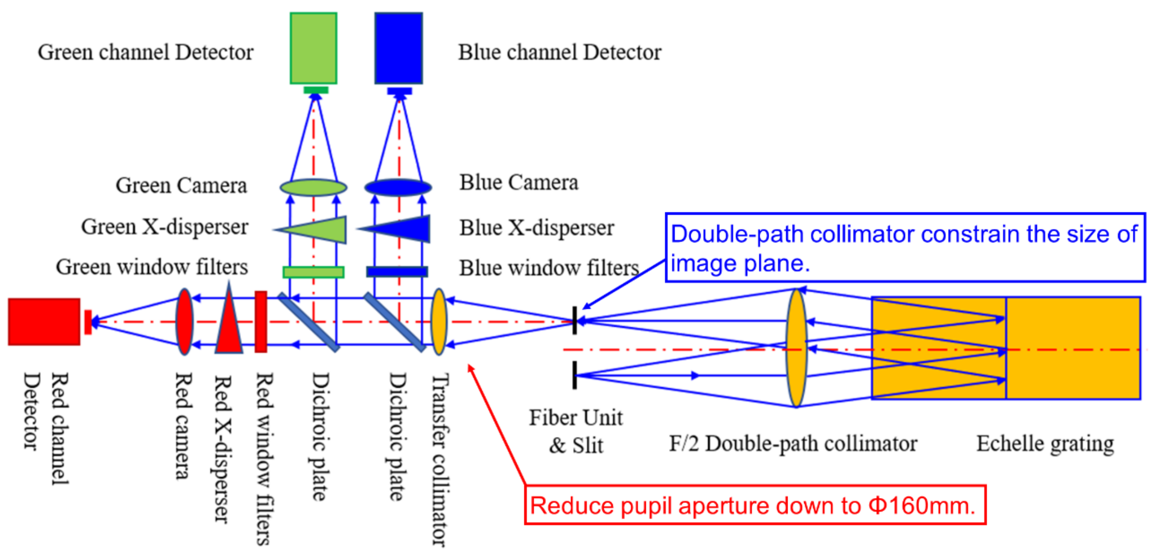

Figure 3. Schematic diagram of a transmissive design based on echelle grating

For high diffraction efficiency, the echelle grating should be placed under the quasi-Littrow condition. Due to its reflective diffraction, the input and dispersed lights are hard to separate in a collimated path. As a result, the spectrograph has to adopt a similar white-pupil system to split three spectral channels in another collimated path. Figure 3 shows a refractive optical system used for this design. A double-path collimator images multi-object spectra at the first focal plane near the slit. After which a transfer collimator reduces the collimated aperture to 160 mm in diameter to minimize the clear aperture on the beam splitters and the cameras. Finally, each spectral channel employs a small prism to separate two spectral orders and a filter to select the scientific-interesting wavelength ranges, or "working windows" (Figure 4). Limited by the spatial dimension, the spectrograph can only accommodate less fibers.

For further comparison, Table 4 lists the main parameters of the new transmission design and the 2018 catadioptric design used before. The multiplexing capability and the window bandpass are lower than the previous designs based on the grisms.

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They are regarded as the cost of using echelle grating. It needs two adjacent spectral orders to cover a comparable wavelength range with respect to the required working windows. We consider this new design with a lower multiplexing capability is reasonable trade in order to reduce the technical challenges related to the grism design..

Table 4. Main parameters of two designs for the spectral resolution of R=30K

Parameters	Catadioptric Design	(New) Transmission Design
Spectral Resolution	R_B=30K, R_G=30K, R_R=30K	R_B=30K, R_G=30K, R_R=30K
Dispersion requirement	$mN \geq 3e+6$ ($m = 1$)	$mN \geq 3e+6$ ($m = 43 - 98$)
Multiplexing capability	578 objects per spectrograph, 2 spectrographs	~90 objects per spectrograph, 12 spectrographs
Fibers	Φ0.75”	Φ0.75”
Spectral channels	B: 360 nm - 420 nm G: 420 nm - 580 nm R: 580 nm - 820 nm	B: 360 nm - 420 nm G: 420 nm - 580 nm R: 580 nm - 820 nm
Window bandpass	$\lambda/22$ @ R = 30K	$\lambda/40$ ~$\lambda/24$ with wavelength
Optical system	Conventional MOS	White pupil
Collimated aperture	Φ280mm (Reflective) F/2.05	Φ240mm (Transmission) F/2
Dispersers	‘Diamond’ grism, $\theta b = 53.9°$, 5800 l mm^{-1}	R2.6 echelle, 52.67 l mm^{-1} 3 prisms, apex angle = 17°
Cameras	Focal length: 474mm, F/1.69	Focal length: 288mm, F/1.8
Detectors	6K × 6K pixels, 15 μm $pixel^{-1}$	4K × 2K pixels, 15 μm $pixel^{-1}$
Sampling rate	4.3 pixels	4.7 pixels

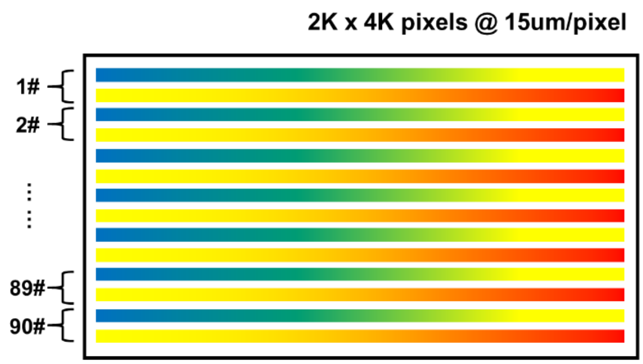

Figure 4. Spectrum pattern by echelle grating

The new design has another advantage in switching the working windows remotely and without replacing dispersers. The spectrograph can provide any two adjacent spectral orders by implementing rotating the filter wheels (Figure 3). It is quite different from the physical method of changing the dispersers in the grism design, which requires a much longer downtime between different observing modes. With this window-switching method, the spectral dimensions on the detector change with their free-spectral-ranges in a different orders (Figure 5).

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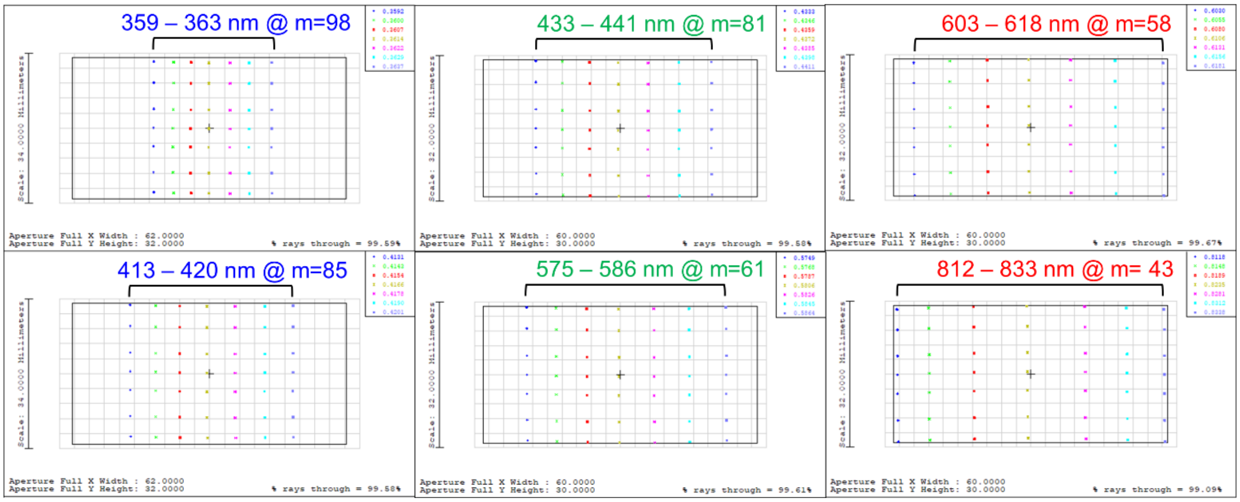

Figure 5. Multi-object spectrum at diffraction orders

3.2 Optical Performance

The optical system consists of many lenses to correct aberration and keep similar image quality at different orders. All of the glass materials have high transmission efficiency over the full wavelength range from 360 nm to 820nm. The spot diagrams in Figure 6 indicates that the preliminary design basically meets the sampling requirement of 4.7 pixels. In the next phase, the optimization aims to reduce the lens sizes and increase space for the fiber unit at the slits. Figure 7 shows that a triangular prism folds the optical path to avoid the mechanical interference between the fiber unit and the transfer collimator. And the fibers are located in an arc curve on the slit plane to “straighten” the spectra on the science detectors among all fibers.

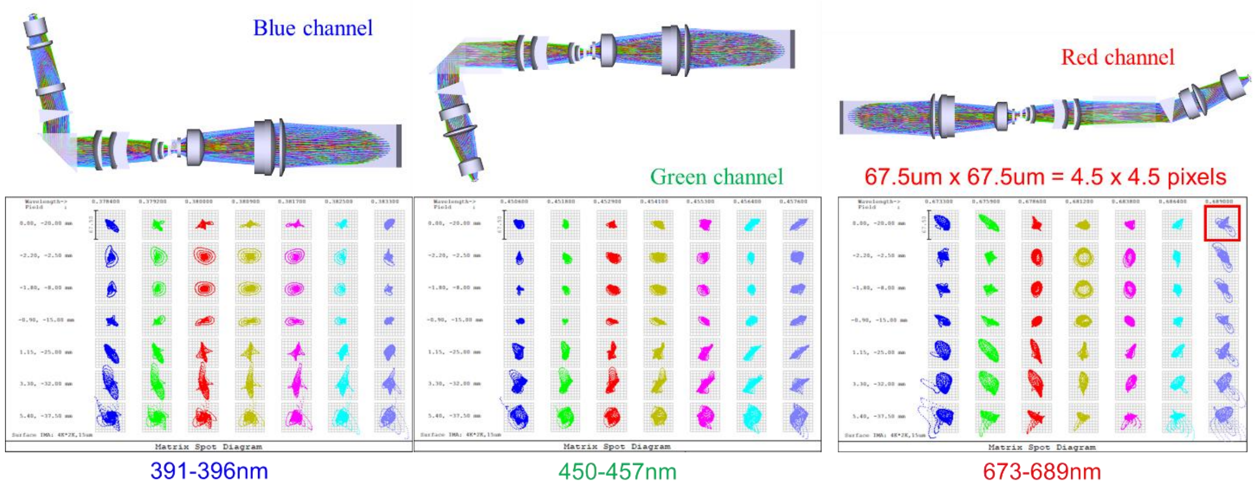

Figure 6. Spot diagrams of three spectral channels

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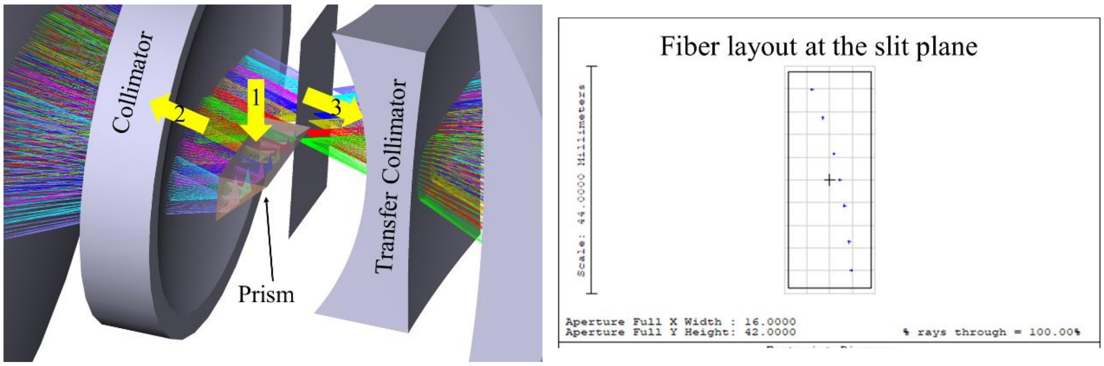

Figure 7. Detailed design near the slit (Left: optical path, Right: fiber layout at the slit plane)

The instrument throughput given by this new design is shown in Figure 8. Compared with the requirement given in Figure 2, it indicates that the current optical system can observe the targets with the magnitude of 19.5, at most of the wavelength range. The throughput at the blue channel should be enhanced by further optimization since the echelle gratings get lower diffraction efficiency than the theoretical one of the grisms[17]. It highlights the importance of realistic technical feasibility in fabrication again.

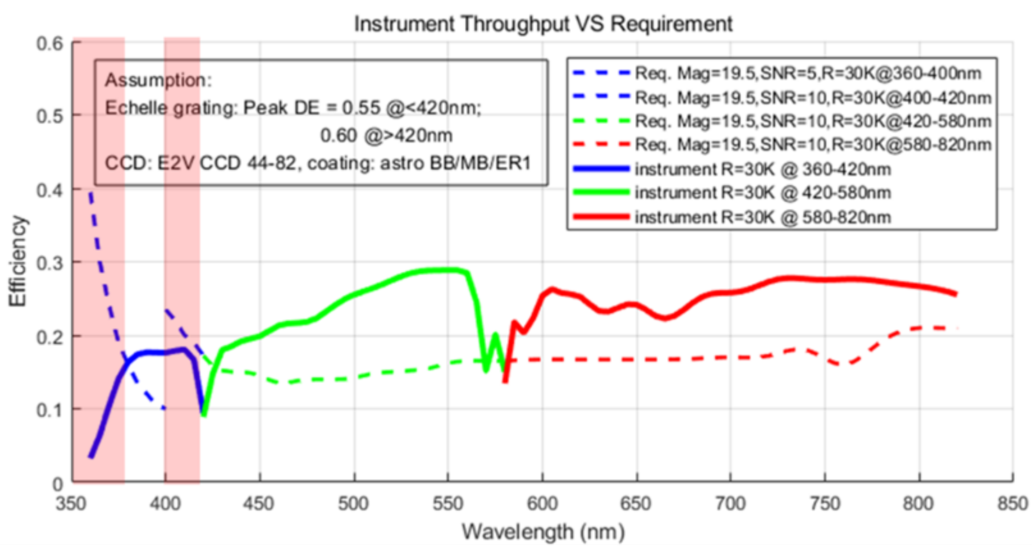

Figure 8. Estimation of instrument throughput of the new design

4. SUMMARY

The MSE-HR spectrograph is a quite challenging astronomical instrument for the multi-object spectroscopic survey. Much knowledge has been learned from the different designs since 2016. SWG and PO will make the design selection through an overall balance between science and technology. Some points are summarized here from the new design: (1) The original intention of using echelle grating is a technical solution to the difficulties in grism fabrication, and the design team note that the performance of instrument throughput is affected. (2) The most significant gain in the current optical design is modifying the window bandpass in each arm by remotely adjusting the bandpass filters and the camera orientations by

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motorized mechanism without changing additional optical elements, especially the disperser. (3) The new HR spectrograph configuration has a lower multiplexing capability. The PO has to justify the cost-benefit trade and operational impacts of having more spectrographs.

ACKNOWLEDGEMENTS

This work progress introduced in this paper is supported by the Chinese Government Scholarship, Grant No. 201704910452, and the National Natural Science Foundation of China (NSFC), Grant Nos. 11773047, U2031144. The authors give sincere thanks to the collaborators who gave much support during the design phase.

The Maunakea Spectroscopic Explorer conceptual design phase was conducted by the MSE Project Office, which is hosted by the Canada-France-Hawaii Telescope. MSE partner organizations in Canada, France, Hawaii, Australia, China, India, and Spain all contributed to the conceptual design. The authors and the MSE collaboration recognize and acknowledge the cultural importance of the summit of Maunakea to a broad cross section of the Native Hawaiian community.

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