Mauna Kea Spectrographic Explorer (MSE): A New Optical 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 into an 11.25m multi-object spectroscopic facility with a 1.5 square degrees field of view. It will get the ability to simultaneously measure 4,332 objects with two spectral resolution modes respectively low/moderate resolution of R=3,000/6,000, and high resolution of R≥30,000. Multi-object high resolution (HR) spectrographs take the challenge of simultaneously producing a thousand high-resolution spectra respectively at blue, green, and red channels. A few different optical designs have been investigated deeply by scientific and technical groups since 2018. With the trade-off studies between science cases and technical capability in dispersers, the paper describes a new design proposal based on using the echelle gratings and taking reference to the industrialized production process. It enables to reduce the technical risk in dispersers and switch the observing wavelength bandpasses quickly by sorting filters.

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

INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE) project [1] will transform the CFHT 3.6m optical telescope to an 11.25m multi-object spectroscopic facility with a 1.5 square degrees field-of-view. It will get the ability to simultaneously measure 4,332 objects with two spectral resolution modes respectively low/moderate resolution (LMR) of R ≥ 3,000/6,000, and high resolution (HR) of R≥30,000. With this impressive capability, the telescope almost can complete a full SDSS Legacy Survey every 7 weeks.

Nanjing Institute of Astronomical Optics and Technology (NIAOT) of the Chinese Academy of Sciences (CAS) has collaborated with the MSE project office and Canada-France-Hawaii Telescope (CFHT) to investigate the optimal design for the multi-objects high-resolution spectrograph since the project workshop held at the Paris observatory in 2015. This work takes on the challenge of simultaneously producing a thousand high-resolution spectra respectively at blue, green, and red spectral channels at a high resolution of R~30,000 originally. We reported a catadioptric design at the SPIE conference in 2018 [2], to achieve the required resolution and make every science object's spectrum parallel to each

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other on the detector. This design employs a large grism in every spectral channel, see Fig. 1. The line density is up to 6,000 l/mm in the blue channel, and the corresponding disperser area is also up to 700mm × 320mm. The grism fabrication and installation become much more difficult due to these disperser parameters [3]. It prompted us to look for alternative designs. After a further discussion around this technical issue with the project office, the MSE Science Team group opted for a lower requirement of spectral resolution (R≥30,000). We traded alternate optical designs in the past years and reported the result of our trade-off study at the last conference in 2020 [5]. The proposed design is based on the use of echelle gratings to avoid the technical problem of large grisms. The echelle gratings are widely used in single-object high-resolution spectrographs to achieve broadband by its multiple diffractive orders. The proposed design put the echelle grating in the main collimator and then divides the dispersed light into three spectral channels, finally getting the required spectra by specific filters, see Fig.2. However, we realized we can improve the image quality and spectrograph efficiency by simplifying its complicated optical system. Subsequently, we optimized the optical design along this idea.

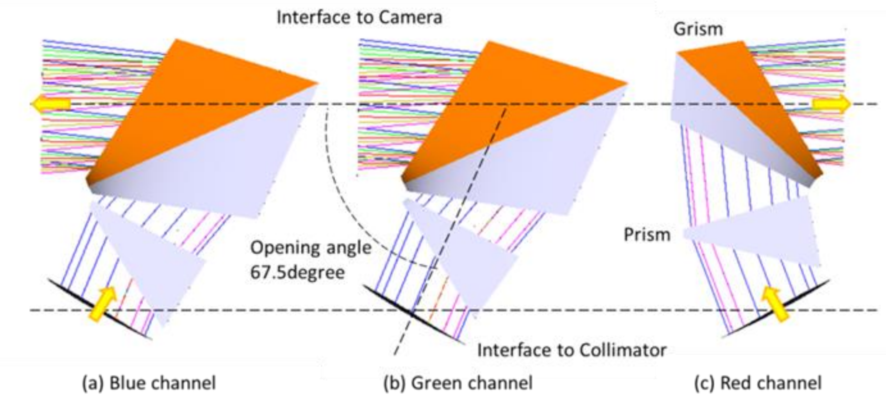


Figure 1. Design of the combination with grisms and prisms in 2018

(e.g., the green grism requires a grating area of 320mm × 700mm between two pieces of triangle prisms.)

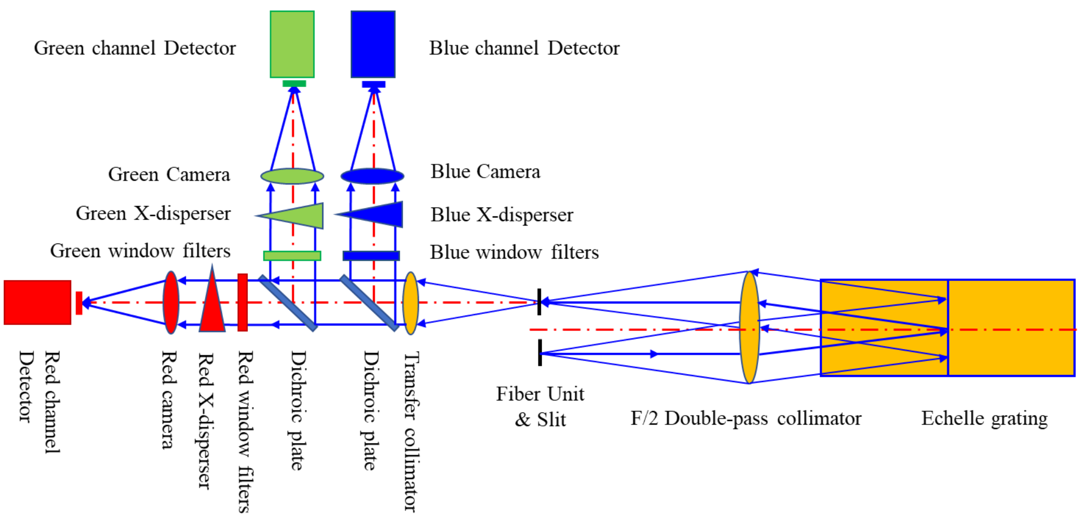


Figure 2. Schematic diagram of a transmissive design based on echelle grating in 2020

The optimization work has some clear objectives listed below.

(1) Accommodating 1084 fibers in total, each one has a sky aperture of 0.75asec or larger.

(2) Spectral resolution of R≥30,000 in blue, green, and red channels.

(3) Window bandpass is not narrower than 1/30 of the central wavelength.

(4) Instrument sensitivity: SNR≥5 @＜400nm, SNR≥10 @≥400nm when observing V=19-19.5 targets with a long exposure of 1 hour. The requirement of instrument throughput is calculated and shown in Fig. 3.

(5) Simplifying the optical system to improve its image quality and throughput.

(6) Looking for a simple method to switch remotely bandpasses during the observation.

(7) Taking full use of modularization and industrialization in instrument production.

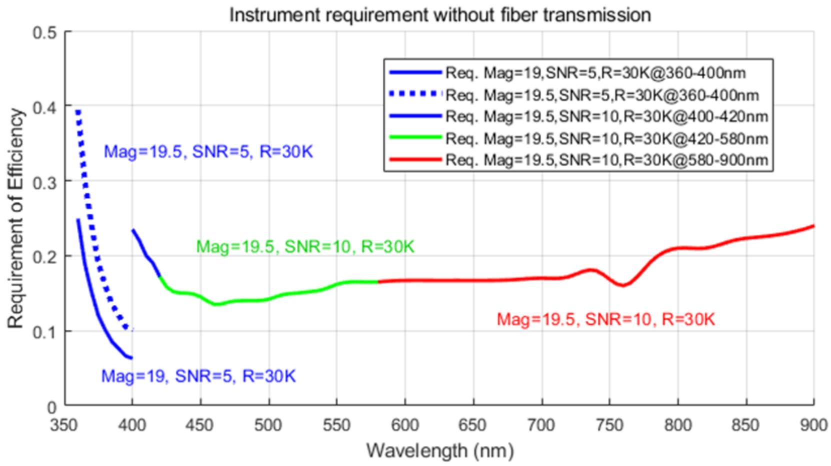


Figure 3. Requirement of instrument throughput

In this paper, we propose an optimized design that utilizes a pre-optic module before similar double-pass optics. Section 2 demonstrates the way to organize the instrument to achieve the requirement of multi-object observation, splitting three spectral channels, and switching their working bandpasses during observation. Section 3 describes the optical design and image quality of each spectral channel. Section 4 discusses the possible technical risks of this proposed design. Section 5 gives a conclusion to explore the way of further work.

OVERALL DESIGN

1.1 Overview

The MSE HR optical design splits the spectrograph spectral range into three spectral channels and accommodates as many fibers as possible. With further studies since 2020, we clearly understand that it is not the best design approach to splits the spectral channels after the main dispersion of echelle grating, and recognize a better solution is to split the light into three spectral channels before the main dispersion. It results in every spectral channel must employ an independent echelle grating. Although the instrument cost would increase, every spectral channel gets a chance to define its spectral resolution optimally according to the scientific requirement. There are possibly two options, adding the dichroic plates after slit inside the spectrograph or employing pre-optics at the outside of the spectrograph, respectively. The former solution requires a complicated optical structure around the slit and three spectral channels are still connected together partially by the physical optical path. It’s obviously not the best solution for our spectrograph when we compared connecting three spectral channels with fibers in conjunction with relay-optics. The latter solution is so flexible and makes the optical design much easier. The pre-optics can slow down the focal ratio of F/2 certainly and then splits light into three channels by coupling it to new fibers. On the other hand, there is possibly some additional space to add a shuttle, the filter wheels for the specific working windows, and a calibration port. Based on these considerations, we propose the following design for the overall instrument and a single-channel spectrograph.

1.2 Instrument architecture

In this design, we divide the composition of our target instrument into three levels, HR spectrograph, spectrograph unit, and channel spectrograph respectively. The MSE telescope feeds our HR spectrograph by coupling evenly all the fibers into 11 identical spectrograph units. A single spectrograph unit contains pre-optics, channel fibers, and three channel-spectrographs, see Fig.4. This instrument configuration allows every channel-spectrograph to observe up to 100 targets simultaneously with a low cross-talk of 1% between any two adjacent spectra. Table 1. Margins and print area specifications.

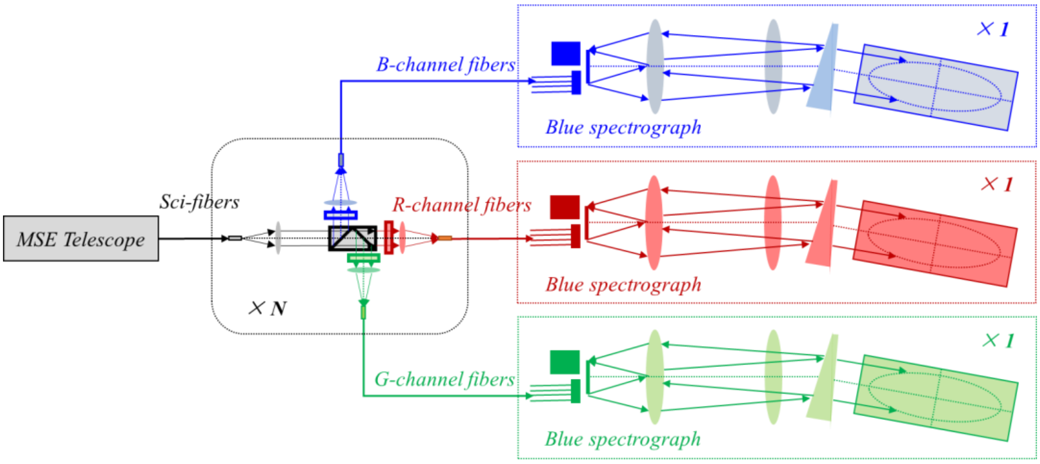


Figure 4. Architecture of single spectrograph units

Benefiting from this configuration, the channel-spectrographs are so similar as to be designed in a modularized way. It could be put into an identical instrument chamber with a dimension of 0.9m×0.9m×3m. Thus, a matrix of structural frames with 11×3 instrument ports can integrate the whole HR spectrograph. Fig. 5 shows a feasible instrument architecture composed of five parts, including science fibers from the telescope, the matrix of pre-optics, channel fibers, the matrix of spectrograph units, and the cryogenic facilities for the scientific detectors.

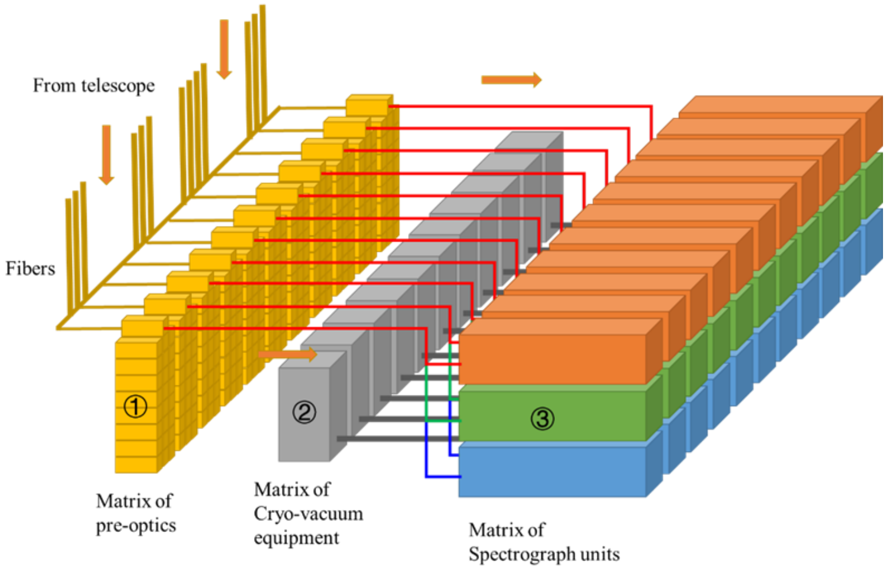


Figure 5. A proposed instrument architecture

1.3 New method of switching working windows

It’s well known that we normally switch working windows (observing bands) by turning the gratings or changing other gratings when the multi-object spectrograph is designed with conventional first-order gratings. It takes some time to align the optical path again after changing the working windows. Thus, the spectrographs are always configured during the daytime instead of the observation night. The new design provides one more option to switch the working windows in the pre-optics. It will allow to do it at night and make the observation more versatile and flexible. The operation can be completed in three simple steps, as below (Fig. 6).

(1) Select working windows by rotating the filter wheels in the pre-optics.

(2) Rotate echelle grating to compensate for the angular difference among the diffraction orders.

(3) Re-focusing detectors with calibration sources to optimize image quality.

This method doesn’t only take the above advantages but also can relieve the pressure on further maintenance and funding requirements to equip new gratings. It’s believed that scientists would finally benefit from this design.

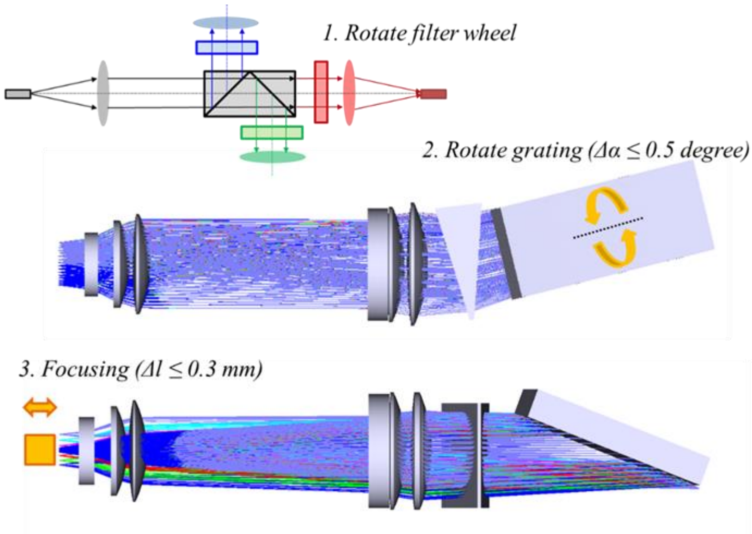


Figure 6. Operation scheme for switching working windows

1.4 An idea for calibration

The telescope for a multi-object spectral survey conventionally requires two modes of calibration, back-illumination for calibrating the fiber positions on the telescope's primary focus and wavelength calibration for the subsequent spectrographs. We can set up a light device to illuminate the fibers backward from the slit but suggest another simple option to project the calibration light from the pre-optics. This idea needs a calibration unit to transmit the different kinds of calibration light to the pre-optics by fibers (Cal. fiber) and a light projector directs the calibration light by a pair of prisms, see Fig. 7. A prism folds the light backward the science fibers, and another prism folds forward the channel fibers. It allows us to make the devices of light projectors and prisms in compact dimensions and share the light with more spectrograph units.

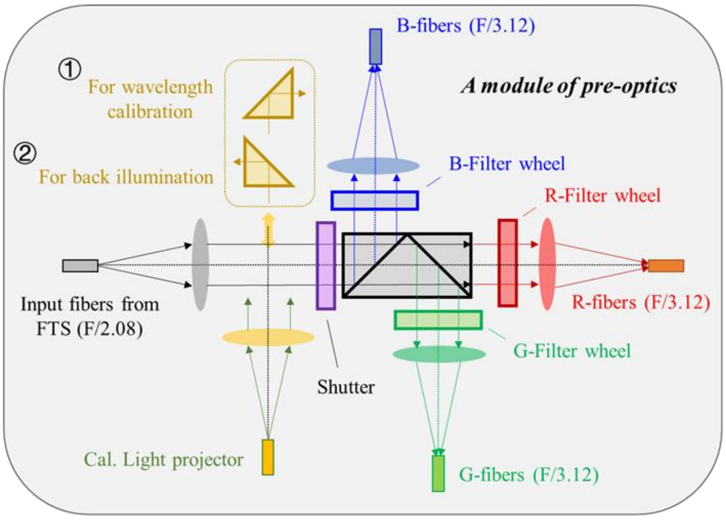


Figure 7. A scheme to inject calibration light from the pre-optics

OPTICAL DESIGN

1.5 Pre-optics

Figure 8 shows a conceptual design for the pre-optics. The size is about 180mm×180mm×40mm. Its field of view is 1.2mm in diameter at the entrance port of science fibers (Φ80um each). This design is able to accommodate 12 fibers or more theoretically in an optional configuration. It depends on the processing technique of coupling efficiently as many pairs of fibers as possible.

In the pre-optics, the focal ratio slows down to F/3.12, and the core aperture of the channel fibers is 120mm in diameter. This slower focal ratio relieves the pressure of designing the double-pass collimator and gives more space among lenses and slit.

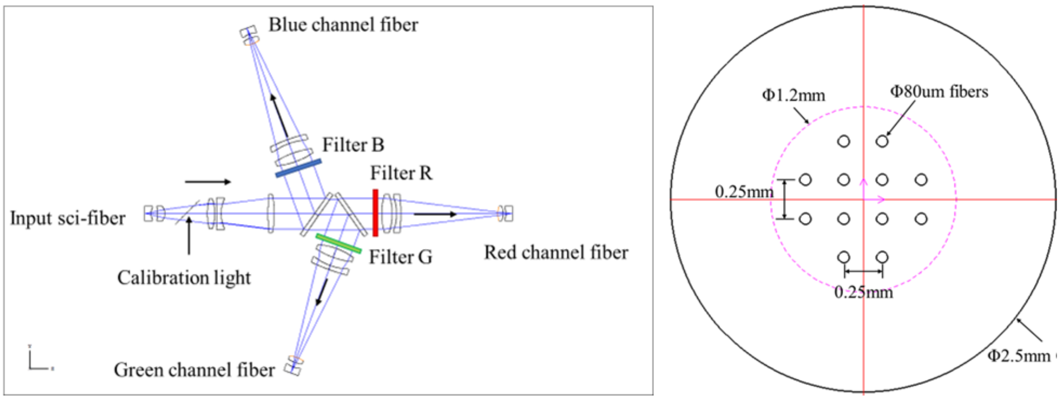


Figure 8. A conceptual design of pre-optics

1.6 Spectrograph unit

The spectrograph unit is expected to run stably at any working window over the full wavelength range from 360nm to 900nm. First, we select the cutting-off wavelength among three spectral channels in accordance with the priority of science cases. The effective band is from 360nm to 420nm in the blue channel, from 420nm to 590nm in the green channel, and from 590nm to 900nm in the red channel, respectively. Second, we filter out the optimal echelle grating by comparing the dispersion and bandpass over the full wavelength range. It's demonstrated from Figure 9 that the R2 echelle grating (63 degrees, 79 l/mm) could fully cover the required bandpass of 1/30 by using 2 diffractive orders instead of 3 orders. It will allow maximizing the number of fibers on the same detectors. Third, the detector chips can be selected by the number of fibers and the maximum of free spectral ranges at three channels. Since double-pass optics is used to design the collimator, the spacing is limited between the detector chip and slit. The multiplexing number of a single channel spectrograph would be 100 fibers when we expect the central interval is at least 2 times FWHM between any two adjacent spectra. Based on this layout, the different detectors are selected for three spectral channels, see Figure 10. It requires a CCD chip with 4K×4K pixels in the blue channel, a chip with 6K×6K pixels in the green channel, and a mosaic chip with 8K×4K pixels in the red channel. The pixel is a size of 15um.

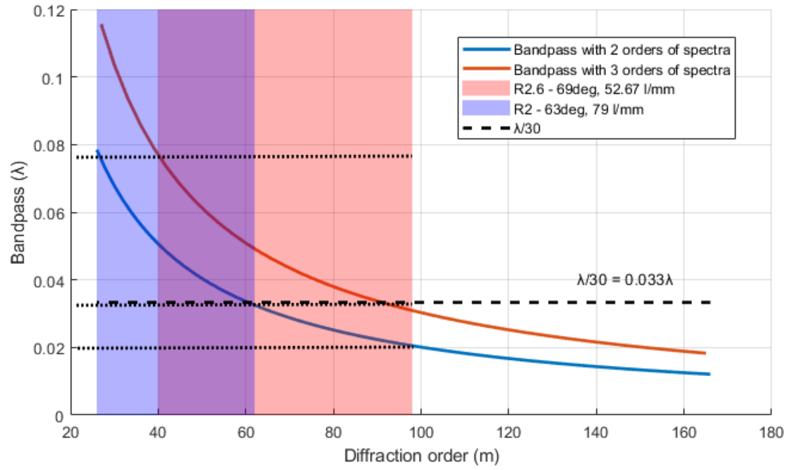


Figure 9. Comparison of bandpass by the gratings and number of diffractive orders

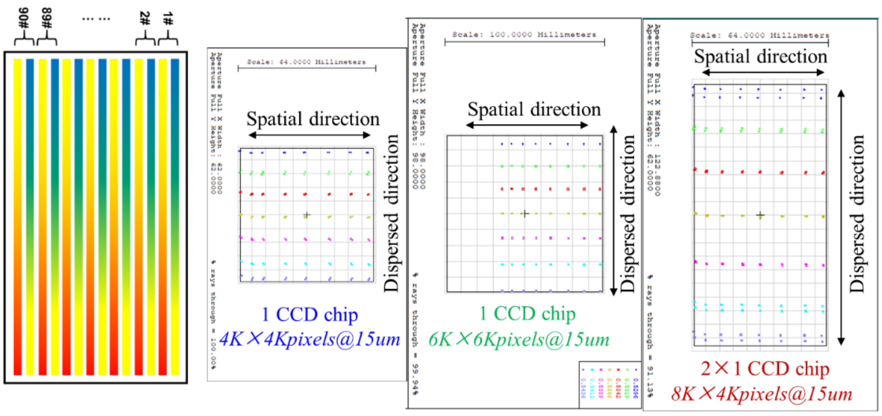


Figure 10. Spectra patterns in three spectral channels

1.7 Channel spectrograph

Three channel-spectrographs adopt similar optical systems with a focal ratio of F/3.12 to provide a large pupil of Φ285mm around the echelle gratings and cover a moderate field of view of Φ6.5 degrees. The optical system contains double-pass lenses as both collimator and camera, a prism as the cross-disperser, and an echelle grating as the main disperser. The double-pass lenses are composed of 1 aspherical lens and 5 spherical lenses with a maximum aperture of Φ420mm. The materials are Fused Silica, CaF2, BSL7, and BSM51Y respectively. The glass size is close to the limit of material production. The last lens is used as a window to insulate a vacuum from an air environment.

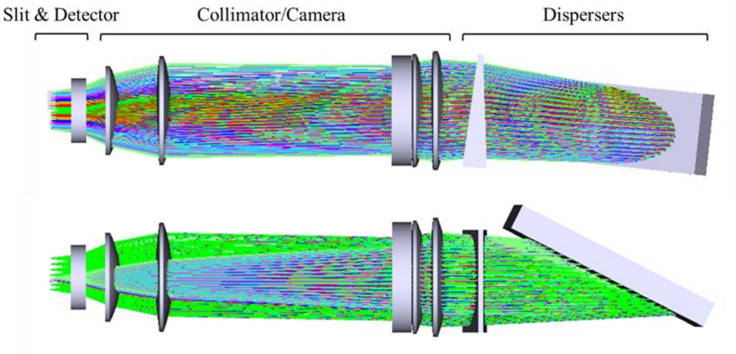


Figure 11. Double-pass optical design for the channel-spectrographs

The double-pass optics put the slit and image plane at two opposite sides of the optical axis. It causes a small incident angle of 2.4 degrees perpendicular to the diffractive plane of the echelle grating. The grating works in the quasi-Littrow condition.

The cross disperser is a fixed prism at the position between the lenses and echelle grating. It separates the spectrum at two adjacent orders to keep the cross-talk at the low level of 1%.

The edge interval is only 8mm between the slit and the image plane. We suggest studying a combined dewar to accommodate both of detector chip and fiber unit at the slit. To reduce the risk of mechanical interference, we set the slit at the plane perpendicular to the image plane by using a folding prism, see Fig. 12. The fibers can be arranged in an arc for making every spectrum parallel to each other at the image plane.

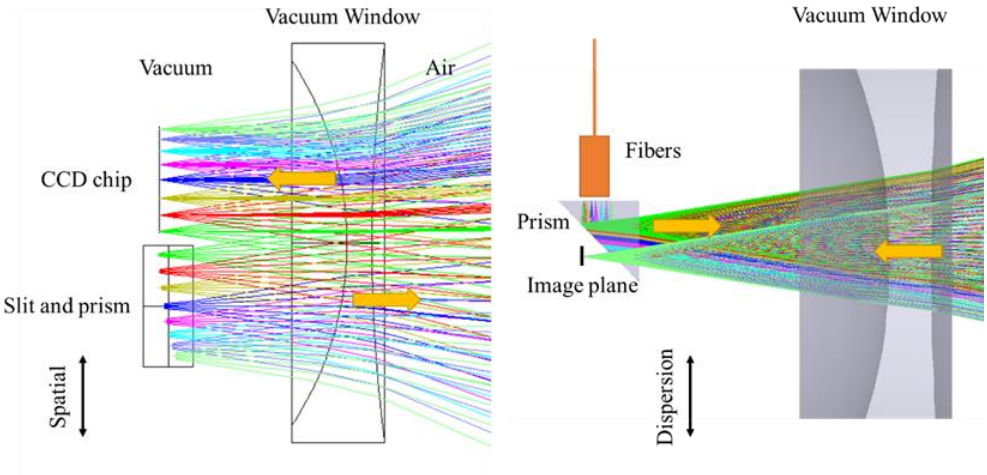
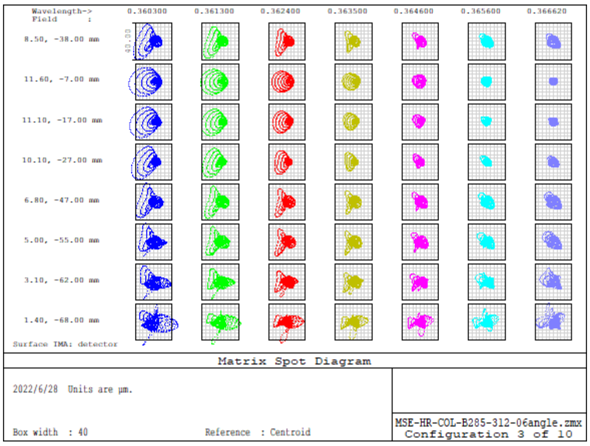


Figure 12. Optical layout of slit and image plane

1.8 Evaluation of performance

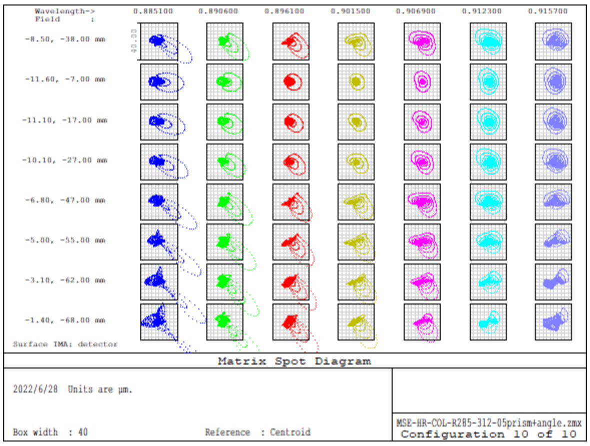
The optical designs achieve good image quality in all three spectral channels. The geometric image is 8 pixels at a single resolved wavelength. With image simulation, its FWHM could be in a range of 6 ~ 7 pixels over the full detector area. It's the potential to add a narrower slit in front of fibers to increase spectral resolution.

Figure 13 shows the spot diameters at the random orders in three spectral channels. The spot is smaller than the scale box of 40um corresponding to the sky aperture of 0.25 arcseconds.



(a) Central wavelength of 360nm at m = 62 in the blue channel

(b) Central wavelength of 593nm at m = 38 in the green channel



(c) Central wavelength of 900nm at m = 25 in the red channel

Figure 13. Spot diagrams of three spectral channels

It's very important for scientific research whether the bandpass met the baseline requirement of 1/30 at every working window. As a result of optical design, the detectors almost cover enough spectrum in all three channels. The bandpass is the sum of the effective wavelength range at every two orders. Figure 14 demonstrates the bandpass from 360nm (m=62) to 900nm (m=25). Most of them meet the requirement very well. The broad bandpass is up to 1/15 in the red channel.

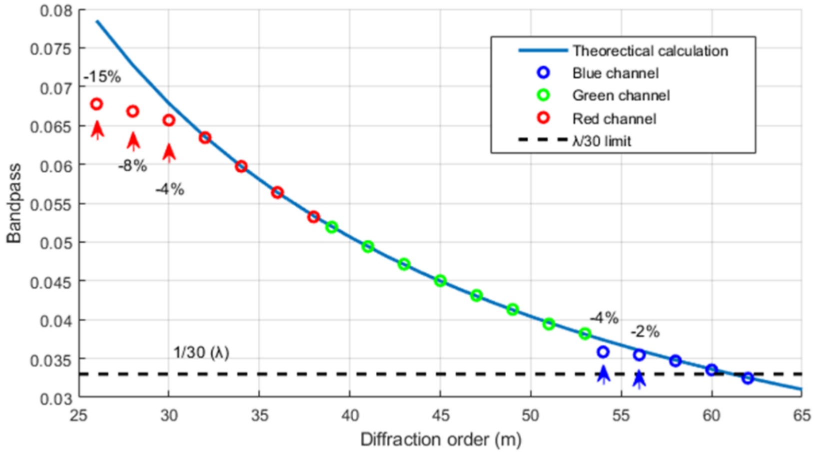


Figure 14. Bandpass of different working windows

With the difference in refractive index, the cross-dispersion changes certainly among all the diffractive orders. This design remains the minimum of central spacing between two adjacent spectra is 2 times wider than the above FHWM (6~7 pixels). It's verified clearly in Fig. 15.

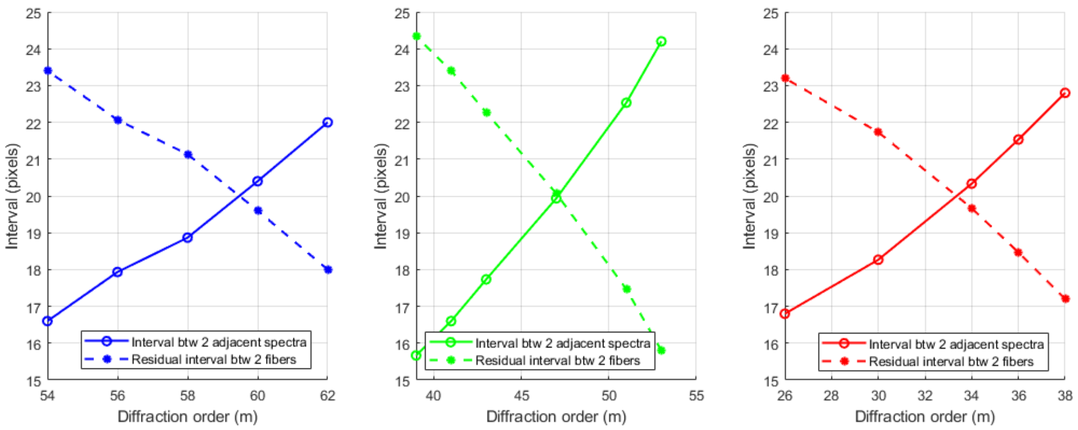


Figure 15. Variation of the central spacing between 2 adjacent spectra

Finally, the optical throughput is estimated by the glass materials, optical coatings, diffraction efficiency, and the quantum efficiency of the detectors. Here, we investigate two kinds of CCD chips, the standard products with optimal coatings, and the special products with IR-enhanced technology of Hi-Rho. The estimation shows us that both kinds of CCD chips enable to meet the requirement of instrument sensitivity given in Fig. 3. With the use of 'Hi-Rho' technology, it feasibly increases the total throughput in the red channel.

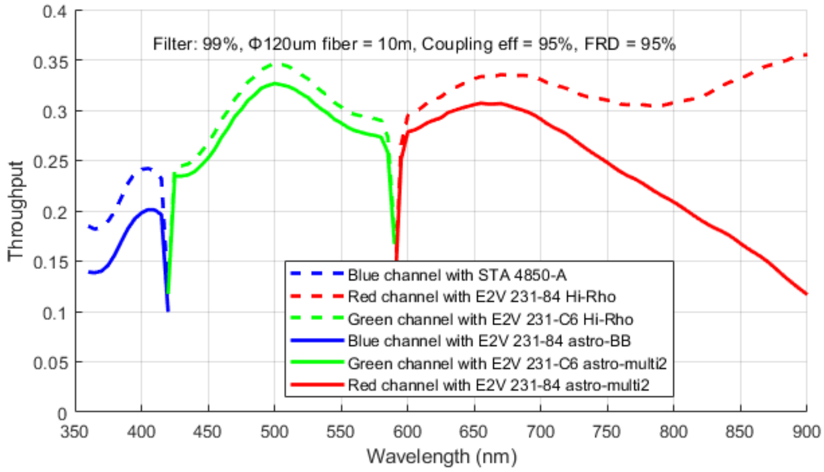


Figure 16. Estimation of instrument throughput

TECHNICAL RISKS

Compared with the previous design based on the large grisms, the proposed design takes obviously has three advantages and a disadvantage. Its advantages contain the use of conventional echelle gratings, a new method of switching working windows, and the lowest cost request for maintenance and changing working windows. The disadvantage is quite a high cost in the instrument development because every spectrograph unit has a weak multiplexing capability of accommodating more fibers. 11 spectrograph units require too much cost even if they would be made in an industrialized way. Besides these, we still find some technical risks to further study in detail.

(1) The most important part is the combined dewar for the detector and the slit. It hardly relieves the pressure on fibers at the air-vacuum interfaces.

(2) The specific filters are used to cut off the rest spectra out of the working window. It exists an obvious risk to generate straylight from the other diffractive orders.

(3) Supply of large glass materials and echelle gratings. It shall be further discussed with the vendors.

CONCLUSION

The double-pass optics is a mature structure that has been used widely by some astronomical spectrographs for more than 40 years [6]. It has been optimized for different kinds of optical systems like the 'white pupil' used for a single-object high-resolution spectrograph. The present design is another attempt to find the optimal solution for the MSE HR spectrograph. The large aperture is still critical to affecting its optical design. We will take more tries to reduce the pupil aperture with some advanced technologies in the coming time.

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