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The HR image slicer for GNIRS at Gemini North: optical design and performance

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ABSTRACT

GNIRS (Gemini Near-InfraRed Spectrograph) is a multi-function spectrograph at Gemini North telescope offering four observational modes in the spectral range of 0.8 to 5.4 µm. It provides 2-pixel spectral resolutions from 1,200 up to 18,0000 and has single disperser and cross-disperser modes yielding simultaneous spectral bandwidths from 40 nm to 1,650 nm. GNIRS presented three existing modes: long-slit (50-100" slit), cross-dispersed (5-7" slit) and low resolution (LR) Integral Field Unit (IFU) (3.15" x 4.80") and it is now being upgraded with a fourth mode allowing high resolution (HR) IFU spectroscopy using an image slicer optimised for fully adaptively corrected images over a field of view of 2.25 arcsec^2 (1.80" x 1.25") covered by 25 slices of 410 µm width offering a spatial sampling of 0.05 x 0.05 arscec^2 with a diffraction limited optical quality.

The proposed layout meets specifications and some challenging design constraints: it shall be contained within the same envelope defined by the LR image slicer (0.1 x 0.2 x 0.1 m^3), the input and output focal-ratios of both image slicers shall be the same and at exact positions but providing different anamorphic magnifications and preserving the optical quality. The length of the generated slit will be similar to the length of the slit in long-slit mode to maximise detector use and avoid vignetting. This communication presents the optical design and performance of the high resolution image slicer compliant with all specifications and constraints and it shows some design adaptations adopted in order to facilitate its manufacturing in metal at Durham University.

Keywords: GNIRS, image slicer, high resolution spectroscopy, Gemini North, IFU, IFS

1. INTRODUCTION

The Gemini Near-InfraRed Spectrograph (GNIRS)[1] is a medium resolution spectrograph at the Gemini[2] North telescope, covering the 0.8 to 5.4 µm wavelength range with two different cameras providing image scales of 0.05 and 0.15 arcsec per pixel. GNIRS presented three existing modes: long-slit (50-100" slit), cross-dispersed (5-7" slit) and low resolution (LR) Integral Field Unit (IFU) (3.15" x 4.80"). GNIRS lost its low resolution image slicer in 2007 due to a thermal runaway. The same image slicer[3,4,5] has recently been manufactured at Durham University with enhanced performance[6] and it is currently being commissioned at the Gemini North telescope. GNIRS is now being upgraded with a fourth mode allowing high resolution integral field spectroscopy using a high resolution (HR) image slicer. This has been designed, and it is under manufacture and tests at Durham University. These two image slicers will equip GNIRS with a powerful integral field spectroscopic capability. The Low-Resolution (LR) IFU is designed to sample the 20th percentile PSF obtained with just tip-tilt correction from the telescope secondary (0.35" FWHM in K-band), whereas the High-Resolution (HR) IFU is optimised for fully adaptively corrected images.

2. SPECIFICATIONS

Both, the LR and the HR image slicers of GNIRS cover a spectral range from 0.8 to 5.4 µm. The HR image slicer will be used with the GNIRS Long Cameras (blue and red). The field of view for the HR image slicer is 1.80 arcsec x 1.25 arcsec, divided in twenty-five slices and generating a slit with 900 spatial elements. The spatial sampling is 0.05 arcsec x 0.05 arcsec.

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These specifications are presented in **Error! Reference source not found.** and are the result of a trade-off between several different factors:

- The desire to significantly improve on the spatial sampling of the LR IFU (0.15 arcsec/spaxel)
- The desire to properly sample an optimally AO-corrected image in the H-band (EE(50%) ~ 0.05 arcsec diameter)
- The desire to optimally exploit the limited number of detector pixels on the Aladdin-III detector arrays (1024x1022)
- The desire to have a field-of-view aspect ratio of ~1.5:1 to allow spatial dithering and some capability to observe linearly extended sources
- A balance between the number of slices and pixel gaps between slices on the detector.

Table 1. Specifications for the design of the HR image slicer.

Specifications for the HR image slicer	
Spectral range	0.8 to 5.4 μm.
Field of view	1.80 arcsec x 1.25 arcsec
Spatial sampling	0.05 arcsec x 0.05 arcsec
Number of spatial elements	900
Output slit length	30.89 mm
Maximum volume	0.1 x 0.2 x 0.1 m^3

3. OPTICAL DESIGN

3.1 Design description

The HR image slicer (and the LR image slicer) is composed of two subsystems: a fore-optics subsystem and an image slicer subsystem. The basic principle is that of the “Advanced Image Slicer”[4]. The Advanced Image Slicer consists of a set of fore-optics which re-image the native Gemini F/16 focal plane at a magnified plate scale, with anamorphic magnification in the spatial and spectral directions. This fore-optics subsystem generates a focal plane which is the entrance of the image slicer subsystem. The fore-optics subsystem is composed of three mirrors: a flat mirror (F1) and two toroidal mirrors (F2 and F3) which produce the anamorphism. The pick-off mirror (F1) has its centre on the focal plane of the telescope and it is used to capture the image and send it to the slicer system. It also acts as a first baffle to delimit the field of view. The two re-imaging mirrors (F2, F3) are used to re-image and magnify the field onto the slicer mirrors whilst providing control in the pupil position. They are also used to change the aspect ratio on the detector so that a square spatial element on the sky is re-imaged on a rectangle of 1 x 2 pixels; this ensures that the effective spatial sampling element on the sky is square, whilst maintaining Nyquist sampling in the spectral direction.

The image slicer subsystem divides the 2-D field of view and reorganises it into a slit with approximately the same length as that for the GNIRS long-slit spectrograph mode (without IFU). The image slicer is composed of three arrays of mirrors, each one with twenty-five mirrors: the slicer mirror array (S1, spherical), the pupil mirror array (S2, spherical) and the slit mirror array (S3, toroidal). The magnification provided by the fore-optics is necessary to allow the slicer mirrors to be of a suitable physical width for diamond machining, and to minimise light losses at the interface between slices. The pupil mirrors reverse this magnification step, so that the overall system is 1:1 magnification at the output slit and the beams enter the spectrograph at the appropriate focal ratio to feed the collimator. The powered slit mirrors ensure that the pupil is correctly re-imaged onto the spectrograph grating. All these design parameters are presented in Table **2** and the optical design is shown in Figure 1.

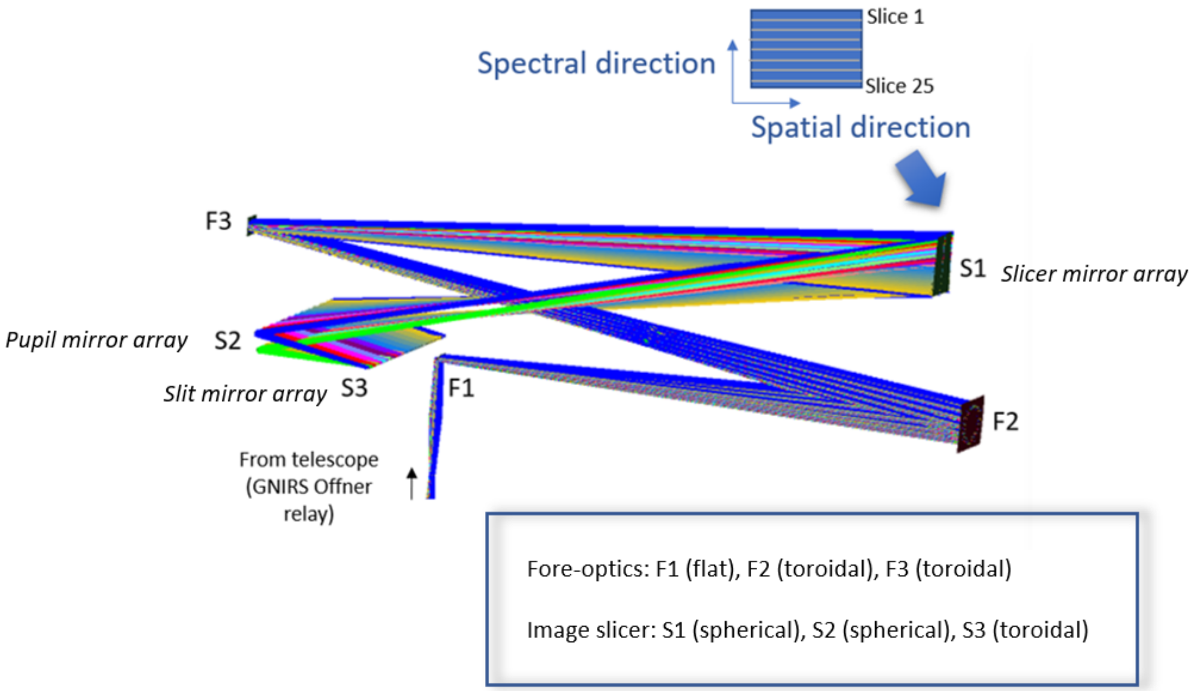


Figure 1. Optical design of the HR image slicer for GNIRS at Gemini North.

The design approach adopted for the HR image slicer closely follows that for the LR image slicer with the following exceptions:

- The magnification of the fore-optics subsystem is optimised for the higher spatial resolution
- The toroidal mirrors F2, F3 have been mechanically designed to allow direct on axis, freeform machining
- The slicer mirror array is designed in a way which allows manufacture as a single part
- The pupil mirror array is configured in two parallel rows to minimise off-axis aberrations
- The slit mirrors present different radius of curvature and different radius of rotation.

Table 2. Design parameters of the HR IFU.

DESIGN PARAMETERS	
Field of View (FoV)	1.80 arcsec x 1.25 arcsec
Telescope effective focal length	128.12 m
Telescope focal-ratio	F/16
Plate scale	1.610 arcsec/mm
Linear size of the FoV at the telescope focal plane	1.118 mm x 0.776 mm
Number of slices	25
Fore Optics magnification along spatial direction	5.687
Fore Optics magnification along spectral direction	13.275
Width of slicer mirrors	410 μm
Physical dimensions of slicer mirrors	6.358 mm x 0.41 mm
Linear size of the FoV at slicer mirror array position	6.358 mm x 10.30 mm

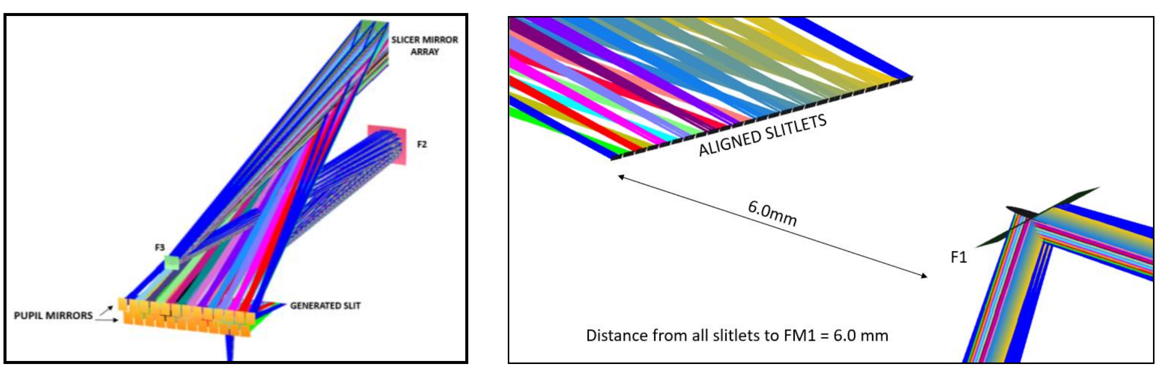
3.2 Optical components

As mentioned in Section 3.1, the image slicer is composed of the fore-optics and the image slicer. The fore-optics is composed by three mirrors: a flat mirror (F1), and two toroidal mirrors (F2 and F3). The image slicer is composed by three arrays of twenty-five mirrors each: slicer mirror array (S1), pupil mirror array (S2) and slit mirror array (S3).

The plate scale at the telescope image focal plane (F/16) is 1.610 arcsec/mm, and the linear size of the 1.80 arcsec x 1.25 arcsec field of view is 1.118 mm x 0.776 mm. The pick-off mirror, F1, is placed at the focal plane. The two toroidal mirrors, F2 and F3, produce the required anamorphism converting the initial linear size of the field of view of 1.118 mm x 0.776 mm into 6.358 mm x 10.30 mm to be covered by twenty-five slicer mirrors. In the direction parallel to the slices, the spatial resolution is defined by the detector pixel size. In the perpendicular direction, i.e. the spectral direction, the resolution is defined by the slice width. If the magnification of the fore-optics in both directions were the same, the slit image would have a width of one pixel on the detector, whereas a two-pixel wide slit is required to avoid under-sampling of the spectra. To resolve this, the re-imaging mirrors of the fore-optics produce an anamorphic stretch of the image on the slicer which is larger in the spectral direction than in the spatial direction. An anamorphic ratio of 2.33 has been chosen, which also accounts for the maximum anamorphic demagnification (1.22) in the GNIRS spectrograph due to the grating tilt of the 110.5 lines/mm grating. The other two gratings, 10.4 lines/mm and 31.7 lines/mm, have anamorphic demagnifications of 1.02 and 1.05 respectively, ensuring that the spectra will remain Nyquist sampled for all gratings.

The linear size of the field of view at the slicer mirror array position is then 6.358 mm x 10.30 mm, and the size of each slicer mirror is 6.358 mm (length) x 0.41 mm (width). Each slice of the field of view follows an optical path defined by the reflection of one slicer mirror into one pupil mirror and one slit mirror generating a piece of the output slit known as slitlet. The slicer stack consists of a series of thin long mirrors (slicer), each with a different tilt around the X and Y axes. Each slicer mirror reflects the light in a different direction towards its corresponding pupil mirror. The slicer mirror array also acts as the field stop to correctly define the field of view. The slicer mirrors (S1) are spherical and all slicer mirrors have the same radius of curvature of 137.5 mm. Within the slicer mirror array the mirrors are distributed with slice #1 at the top, slice #13 being the central slice and slice #25 at the bottom of the array. To facilitate manufacturing as one monolithic component, each slice is offset from the adjacent slice by 0.01mm. This small defocus has no impact on the optical quality because of the large depth of field (slow focal ratio) at the slicer mirrors.

The pupil mirrors are spherical with a same radius of curvature of 35.30 mm. The pupil mirrors are distributed in two rows of 13 (row on the top) and 12 (row at the bottom) mirrors (see Figure 2 (a)) to reduce off-axis distances and minimise aberrations. As its name suggests, the pupil image of the telescope is approximately re-imaged on these mirrors. The positions of the pupil mirrors along the axis defined by the direction of light propagation (defocus) are slightly different to allow the alignment of the slitlets (S3) in the same plane (see Figure 2 (b)) while keeping the magnification identical for all the channels, and the slitlets position in the same plane. S3 reflects the beam towards the spectrograph collimator and re-images the 25 pupils on the diffraction grating. It also acts as a baffle to control stray light. S3 is composed of twenty-five toroidal slit mirrors.



(a) (b)

Figure 2. (a) Distribution of the pupil mirrors in two rows in the image slicer layout; (b) Aligned slitlets at 6.0mm distance from the pick-off mirror F1.

The HR image slicer is contained within the same space envelope defined for the LR image slicer. In both cases, the output slit generated by the IFU is at the same location so there are no variations in the spectrograph performance.
Since the pupil mirrors are placed at different positions along the light propagation direction (defocus, Z-axis), there is a different optical length from the intermediate pupil images (close to the pupil mirrors) and the output slit (spectrograph entrance slit), which is translated into different locations along the Z-axis for the pupils around the diffraction grating. To locate all pupil images on the grating, each slit mirror then requires a different radius of curvature. The slit mirrors are toroidal and thus they present two radii: a radius of curvature and a radius of rotation. The radius of curvature is the radius across the slit (spectral direction) and the radius of rotation is defined along the slit (spatial direction).

For each slice, three field points were defined, covering the centre and the extreme in diagonal. In order to reduce the separation between the footprints on the grating obtained for these three field points, a different radius of rotation per slit mirror is used. This avoids any potential vignetting in the spectrograph due to the existing baffles or apertures. The radius of curvature and radius of rotation of the twenty-five slit mirrors are shown in Table **3**.

Table 3. Radius of curvature and radius of rotation of the slit mirrors of the high resolution image slicer of GNIRS.

Slit mirrors		
Configuration	**Radius of curvature [mm]**	**Radius of rotation [mm]**
1	37.807	31.689
2	40.691	29.526
3	36.895	29.526
4	39.599	28.575
5	36.036	29.811
6	38.570	27.797
7	35.227	29.120
8	37.589	27.163
9	34.460	28.564
10	36.666	26.659
11	33.733	28.128
12	35.790	26.269
13	33.053	27.806
14	34.965	25.984
15	32.414	27.588
16	34.189	25.797
17	31.811	27.465
18	33.463	25.707
19	31.246	27.442
20	32.780	25.704
21	30.727	27.509
22	32.143	25.796
23	30.238	28.000
24	31.548	25.980
25	29.784	27.500

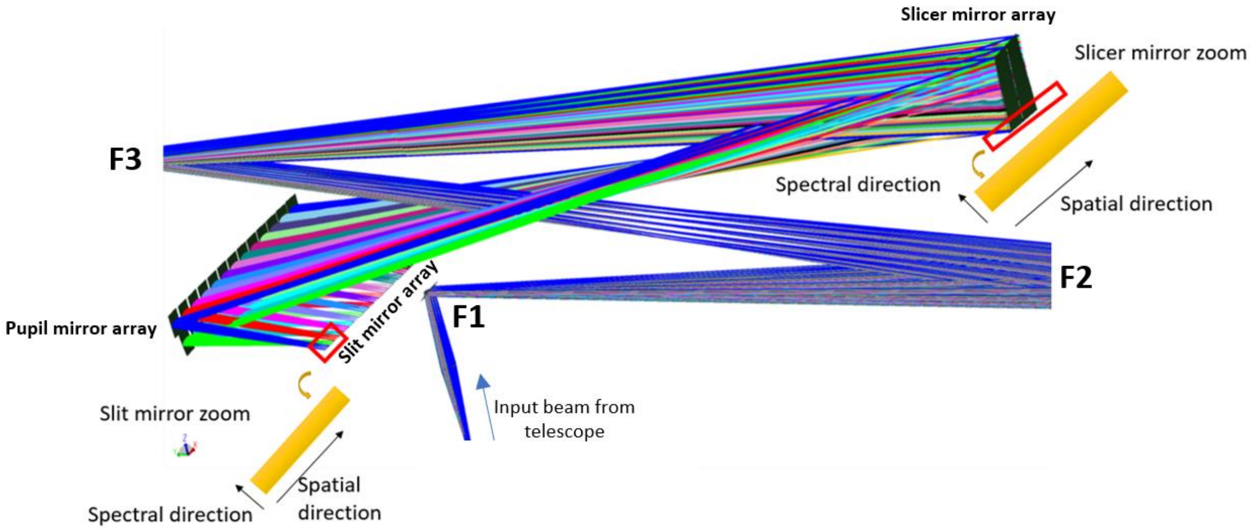


Figure 3. Spatial and spectral directions defined at the slicer mirror and slit mirror (slitlet).

4. DESIGN CONSTRAINTS

For the optimisation of the optical design (Figure 1), first, the fore-optics were optimised to provide a high image quality on the slicer mirrors with the right magnification and minimal distortion. Then the image slicer subsystem components were added for all twenty-five configurations.

The optical design of the high resolution image slicer was also constrained by several conditions imposed by either mechanical interface constraints or the proposed manufacturing method (diamond machining):

- The HR IFU (fore-optics plus image slicer) must be contained within the volume defined for the LR IFU, this is: 0.1 x 0.2 x 0.1 m^3.
- The input and output focal ratios of the HR and LR IFUs will be the same.
- The fore-optics will have an anamorphic ratio of 2.33.
- All slicer mirrors will be spherical with identical radius of curvature.
- All pupil mirrors will be spherical with identical radius of curvature.
- The output slitlets generated by the image slicer will be aligned and will be located at 6.0 mm from F1.
- Slit mirrors will only have tilt angle around one direction. This angle will be the same for all beams associated to pupil mirrors within the same row.
- All slitlets (i.e. the re-imaged slices on the output slit) will have nearly the same pitch and length, which also implies that the gaps between adjacent slitlets are almost the same.
- The length of the generated slit will be similar to the length of the slit for GNIRS long-slit observation mode (with the long camera) to maximise detector use and avoid vignetting.
- The field stop shall be rectangular and at the slicer position.

The proposed design is compliant with all the above constraints. The optical design of the HR image slicer coupled to the GNIRS Long Blue Camera spectrograph is presented in Figure 4.

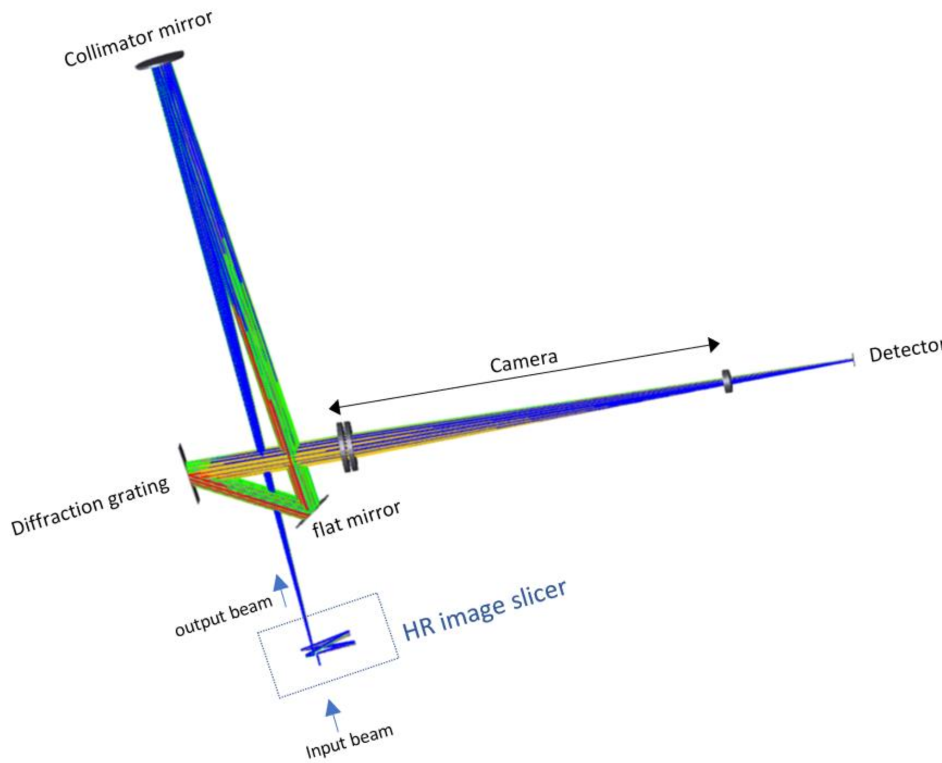


Figure 4. Optical design of the high resolution image slicer coupled to the GNIRS Long Blue Camera spectrograph.

5. PERFORMANCE

The GNIRS high resolution image slicer has a diffraction limited optical quality. There is no vignetting within the HR IFU, including when coupled to the Long Blue Camera spectrograph. The slit generated by the IFU has the same length of that in slit mode (without IFU). The optical performances are described in the next subsections.

5.1 Optical Quality

The optical quality of the HR IFU considering the two sub-systems, fore-optics and image slicer, is diffraction limited across the whole field of view. This is shown in the spot diagram of Figure 5 evaluated at the spectrograph entrance slit position (image slicer output). In this figure, each column corresponds to a slitlet (image of a slice of the field of view at the IFU image focal plane) defined by three field points corresponding to the centre of each slicer and the two opposite corners in diagonal. Twenty-five columns represent the twenty-five configurations (the column on the left is associated to the top slice of the field; the column number thirteen is associated to the central slice and that on the right, to the slice at the bottom). Each configuration is represented in a different colour following the legend on the right. For each field, the circle represents the Airy disk, showing the diffraction limit, within which all rays associated to all fields for all twenty-five configurations are contained.

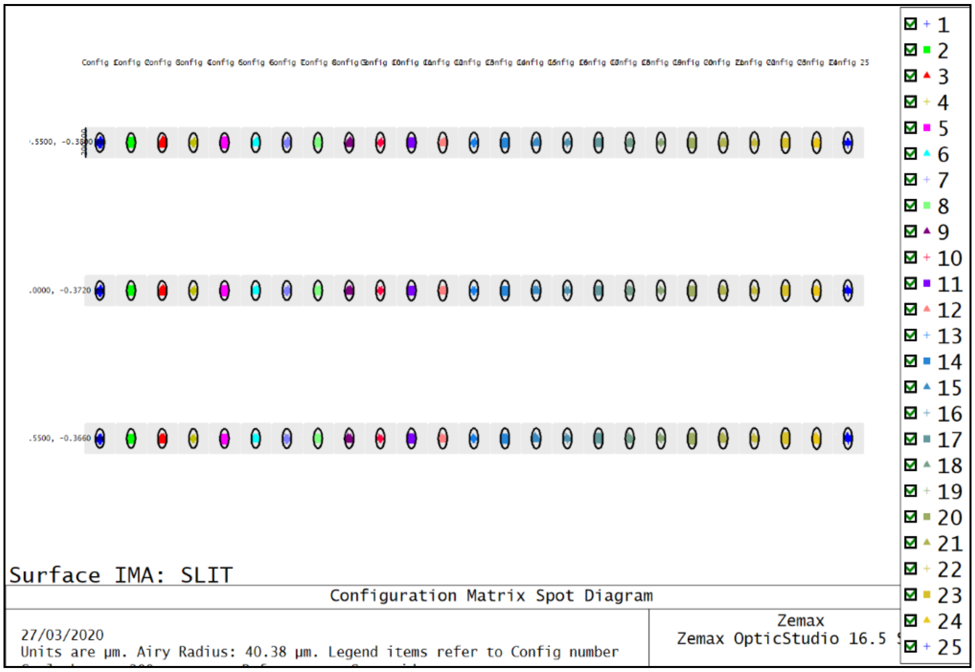


Figure 5. *Diffraction limited optical quality at the output slit for the complete HR IFU design.*

When the HR IFU is coupled to the Long Blue Camera, as shown in Figure 4, the optical quality remains at the diffraction limit, as presented in Figure 6.

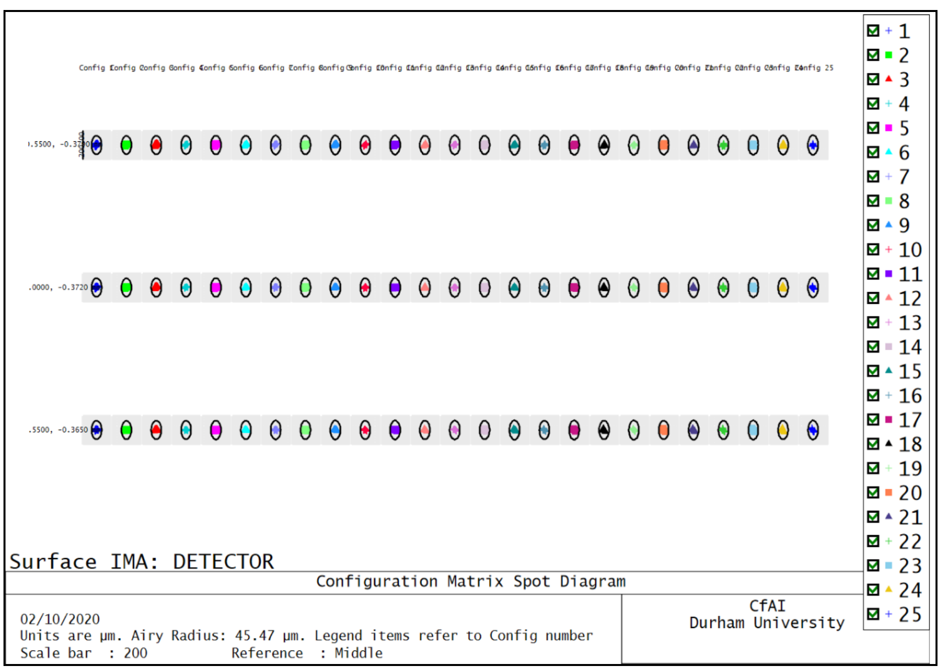


Figure 6. *Diffraction limited optical quality obtained at the detector for the coupling between the HR IFU and the Long Blue Camera spectrograph.*

5.2 Slit length

On the detector, thirty-six pixels are assigned to each slitlet. The output slit is composed of twenty-five slitlets, leading to 900 spatial elements. The space in between two slitlets is approximately constant and is set to be four pixels to minimize crosstalk (the total number of gaps is twenty-four). A view of the twenty-five slitlets obtained from Zemax is shown in **Figure 7**.

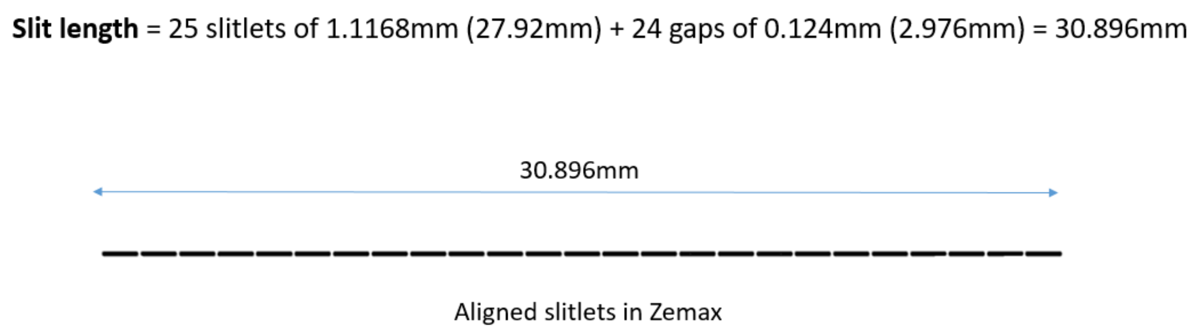


Figure 7. *HR image slicer output slit where all twenty-five slitlets are aligned, with a gap in between slitlets of four pixels (0.124 mm) and a total slit length of 30.896 mm or 996 pixels at the detector.*

5.3 Ensquared energy

The ensquared energy is the fraction of the total power or energy contained within a square aperture of specified half width r, centred on the beam centroid. The ensquared energy for the central field at the slitlet position for configuration 25 (largest off-axis) is presented in Figure 8. At this position, the plate scale is 1.610 arcsec/mm. The 50% and 90% enclosed energy diameters of 0.013 and 0.032 arcseconds are comfortably within the requirements of 0.04 and 0.10 arcsec.

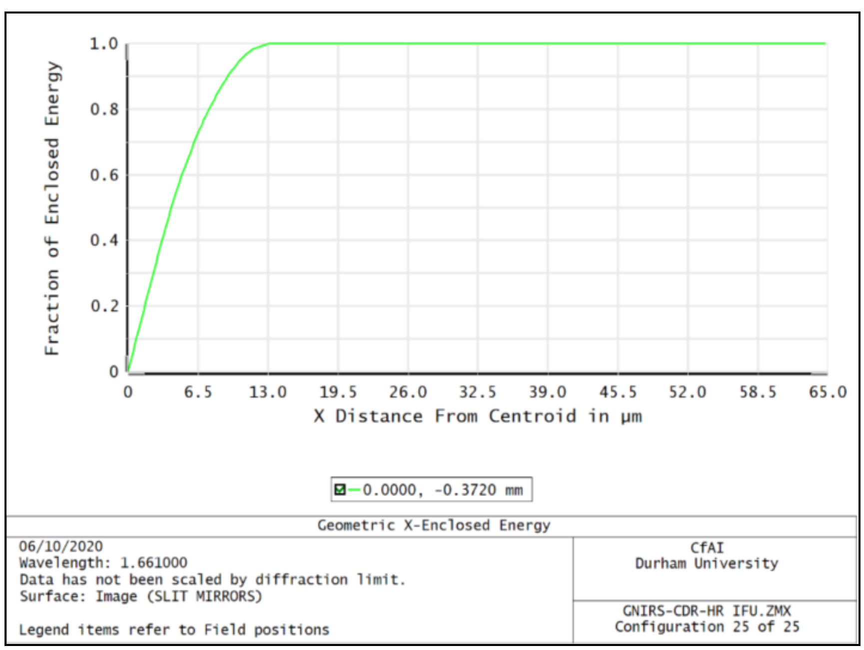


Figure 8. *Ensquared energy at the slitlet position for configuration 25 (largest off-axis).*

5.4 Diffraction effects

The evaluation of the diffraction effects has been done using the "Physical Optics Propagation" (POP) tool of Zemax OpticStudio. This tool propagates a wavefront through the different surfaces of the system. For this evaluation, the central configuration of the HR IFU and the central field was considered at a wavelength of 2.5 µm. This was coupled to the design of the Gemini telescope, by considering initially a flat wavefront at the telescope pupil and a uniform pupil illumination, which is then propagated through every surface of the HR IFU. The diffraction pattern obtained at the slicer mirror is shown in Figure 9 and is dominated by the elliptical Airy pattern due to the anamorphic magnification in the fore-optics.

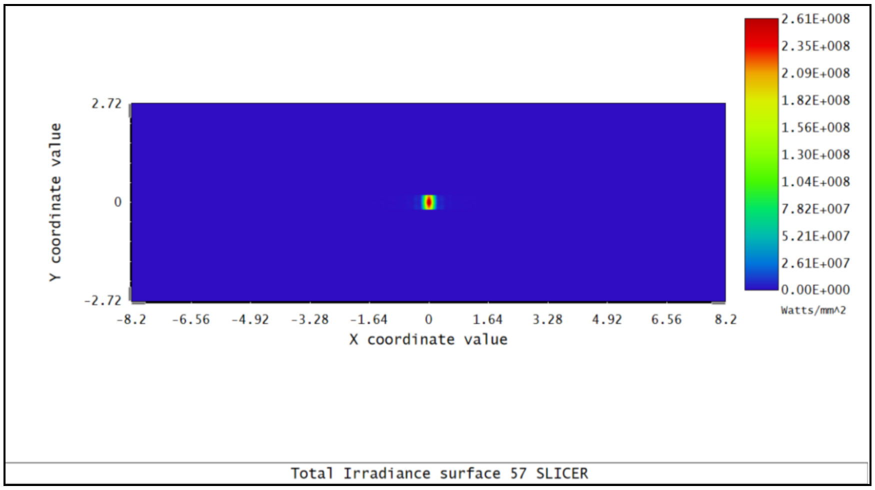


Figure 9. *Diffraction pattern at the slicer mirror for the on-axis field at the central slicer coupled to the GEMINI telescope. Wavelength is 2.5 µm.*

The slicer mirror is a thin rectangular aperture orientated horizontally (along the X axis). Thus, at the pupil mirror a diffraction pattern extended vertically is observed, as presented in Figure 10. For this reason, the pupil mirror size was increased in the vertical direction (Y axis) to maximise the amount of light collected by the pupil mirrors. The size is 2.25 mm along X (horizontal) and 3.0 mm along Y (vertical) within which 96.8% of the energy is contained.

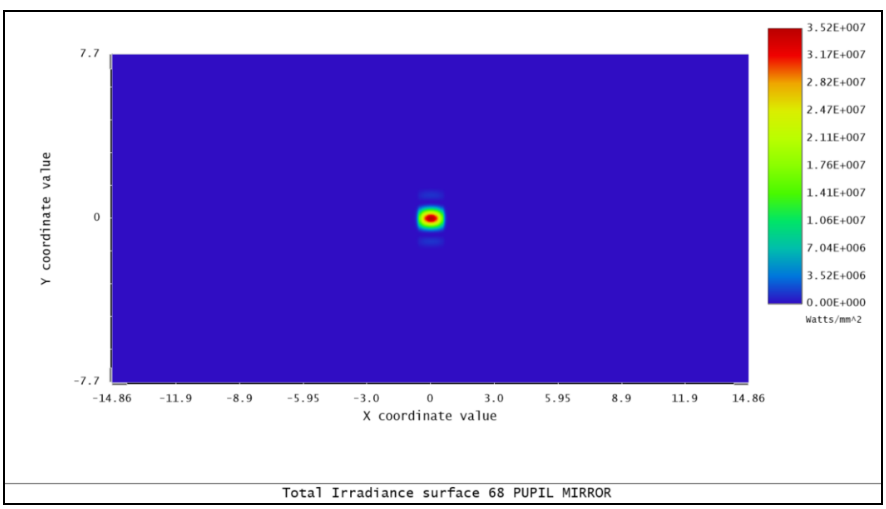


Figure 10. *Diffraction pattern at the pupil mirror for the central configuration and central field for the coupling of the GEMINI telescope and the HR IFU.*

Figure 9 and Figure 10 show the diffraction pattern in linear scale. At the slit mirror the pattern has been represented in logarithmic scale (log-5) to appreciate more detail of the pattern. This is shown in **Figure 11**.

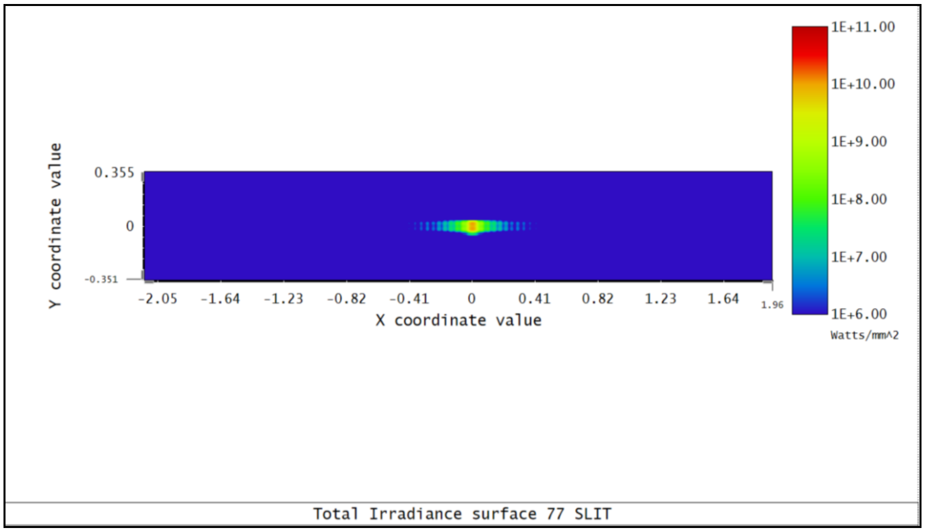


Figure 11. *Diffraction pattern at the slit mirror represented in logarithmic scale.*

6. CONCLUSIONS

The image slicer presented in this manuscript will provide a high resolution IFU mode to the Gemini Near-InfraRed Spectrograph (GNIRS) at the Gemini North Telescope, in Hawaii. Thus, GNIRS will present four observational modes: (1) long-slit (50-100" slit), (2) cross-dispersed (5-7" slit), (3) a low resolution (LR) IFU (3.15" x 4.80") and (4) a high resolution (HR) IFU using an image slicer optimised for fully adaptively corrected images over a field of view of 2.25 arcsec^2 (1.80" x 1.25"), covering the spectral range from 0.8 to 5.4 µm.

The HR image slicer is based on the concept adopted for the LR image slicer and it has been designed for the same envelope volume, 0.1 x 0.2 x 0.1 m^3, presenting the same input and output locations and focal-ratios in both cases, but different anamorphic magnifications. This guarantees the perfect coupling with telescope and spectrograph. The length of the generated slit is similar to that in long-slit mode to maximise detector use and avoid vignetting.

The high resolution image slicer is composed of a fore-optics system, which produces the anamorphic magnification and it is composed of a pick-off mirror (flat) and two toroidal mirrors. At its image focal plane the image slicer is placed, which is composed by three arrays of mirrors: slicer mirror array (spherical), pupil mirror array (spherical) and slit mirror array (toroidal). Each array with twenty-five mirrors. The width of the slicer mirrors is 410 microns and the spatial sampling is 0.05 x 0.05 arscec^2. The design presents an optical quality at the diffraction limit and there is no vignetting at any surface, including those at the spectrograph. The HR IFU optical design presents a diffraction limited optical quality.

This image slicer has been designed, and it is under manufacture and tests at Durham University. Its commissioning is planned later in 2022 and it is expected that this high resolution IFU mode of GNIRS will be available for the astronomical community some time in 2023.

REFERENCES

[1] Elias, J., Joyce, R., Liang, M., Muller, G., Hileman, E., George, J., "Design of the Gemini near-infrared spectrograph", Proc. SPIE Vol. 6269, 62694C (2006).

[2] Diaz, R., Goodsell, D., Kleinman, S., "Gemini Instrument Upgrade Program", Proc. SPIE Vol. 9908, 99082J (2016).

[3] Allington-Smith, J.R., Content, R., Dubbeldam, C. M., Robertson, D. J., Pruss, W., "New techniques for integral field spectroscopy-I. Design, construction and testing of the GNIRS IFU", R. Astron. Soc. 371, 380-394 (2006).

[4] Content, R., "Advanced image slicers for integral field spectroscopy with UKIRT and GEMINI", Proc. SPIE 3354 (1998).

[5] Dubbeldam, C. M., Content, R., AllingtonSmith, J., Pokrovski, S., Robertson, D., "Integral field unit for the Gemini near-infrared spectrograph", Proc. SPIE 4008(2000).

[6] Bourgenot, C. J., Calcines Rosario, A. Z., Dubbeldam, C. M., Sharples, R. M., Diaz, R., Stephens, A. W., "THE LR-IFU FOR GNIRS AT GEMINI NORTH: OPTICAL COMPONENT MANUFACTURING AND METROLOGY", Proc. SPIE, 12188-178 (2022).