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# MAVIS IFU with AO on VLT: Image Slicer Concept and Design

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## ABSTRACT

MAVIS is a future imaging spectrograph for the VLT in which the spectrograph is fed by an IFU. Imager and IFU are fed by Multi-Conjugate Adaptive Optics for the wavelength range 370 nm to 930 nm. The spectrograph will deliver a spectral resolution of more than 4000. The IFU field has a choice of 2 spaxel sizes. It is 9 $\mathrm{arsec}^2$ with 25 mas spaxels and 36 $\mathrm{arsec}^2$ with 50 mas. The design follows the proven concept of Advanced Image Slicer (AIS) as for Gemini NIFS and GNIRS, VLT MUSE and KMOS, JWST NIRSpec, and many others. In the present design, the field is first split in 2 and each subfield is imaged on a slicer mirror array made of long thin mirrors that slice the field into 50 images and send them in different directions to be reimaged side by side on the slit by another mirror array. Additional optics on the slit reimage the pupil at the right place in the spectrograph. Three different options are under study for the slit optics. One is a mirror array of considerably lower cost than the standard design in an AIS. At 25 mas, the spaxels are near the diffraction limit of the longest wavelength. This present challenges not present for seeing limited IFUs as focal ratio degradation due to diffraction by the slices. Another challenge comes from the short minimum wavelength. It is difficult to manufacture efficient reflection coatings for the whole wavelength range. Transmissive fore-optics were then also studied. The field splitter which sends half the field to each of the 2 arms was integrated into the fore-optics. This removes 2 air-glass surfaces from each arm.

**Keywords:** image slicer, integral field unit, VLT, AO corrected instrument.

## 1. INTRODUCTION

Integral field spectroscopy is now universally used on large telescopes. The GMOS IFUs on the GMOS spectrographs and NIFS have been in operation on Gemini for a long time. The VLT presently has two very powerful integral field spectrographs: KMOS and MUSE. While KMOS combines Multi-Object Spectroscopy with Integral Field Spectroscopy with its 24 IFUs, MUSE is the most powerful integral field spectrograph in the world that can be used with adaptive optics. In its high spatial resolution AO configuration, MUSE has a field of 7.5" x 7.5" with a spaxel size of 25 mas. It is however limited in spectral resolution and wavelength range, and has no imaging capability. We are now in the phase-A of a complementary instrument project to make full use of the adaptive optics capability that has been developed for MUSE. It is called the MCAO Assisted Visible Imager and Spectrograph (MAVIS). It will use the laser system and adaptive secondary developed for MUSE combined with its own Multi-Conjugate Adaptive Optics system. In its imaging mode, it will have a 30" field with a pixel sampling of 7.3 mas which give a perfect Nyquist sampling of 2 pixel per $\lambda/D$ at a wavelength of 570 nm. In its spectrograph mode, it will have an integral field unit based on the Advanced Image Slicer concept. MAVIS integral field unit will have a much smaller number of spaxels than MUSE but will complement it in 2 ways: the wavelength range will go from 370 nm to 930 nm then covering the blue part and the resolution will be higher than that of MUSE, more than 4000. Also, because the field of the IFU is much smaller than the field of the imager, it is possible to use both modes at the same time although some of the field of the imager will be vignetted. This is under study. The present paper describes the status of the MAVIS Integral Field Unit design. A preliminary design is presented for one of the options that are under study.

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## 2. PRELIMINARY DESIGN

The preliminary design is based on the concept of Advanced Image Slicer (Figure 1). In the original design, the focal plane of the telescope is reimaged on an array of long and thin mirrors that slice the field in correspondingly long and thin images. This mirror array is called the slicing mirror. The beam from each slice is sent to a mirror that reimages the slice on the slit. A pupil of the telescope is imaged on that reimaging mirror by the slice mirror. This permits to avoid vignetting present on previous slicer designs. A final mirror on the slit reimages the pupil at the right place in the spectrograph. Fore-optics are used to reimage the telescope focal pane onto the slicing mirror. Along the length of the slices, the spaxel width will be determined by the size of a pixel on the detector in the spectrograph spatial direction. In the spectral direction, it is the slice width that determines the size of a spaxel. If the fore-optics simply reimage the field on the slicing mirror with standard optics, the slice width will also be one pixel wide which then gives an undersampled spectral element on the detector. To correct this, the fore-optics magnify the field 2 times more along the width of the slice than along the length which gives a 2 pixel wide slice image on the detector. This is only necessary if the spaxels are not already at least 2 times longer than large as if the slice width is much larger than the pixel size in arcsec on the sky. MAVIS need square pixels of 25 mas and 50 mas so 2 sets of fore-optics that can be exchanged are necessary, one for each size.

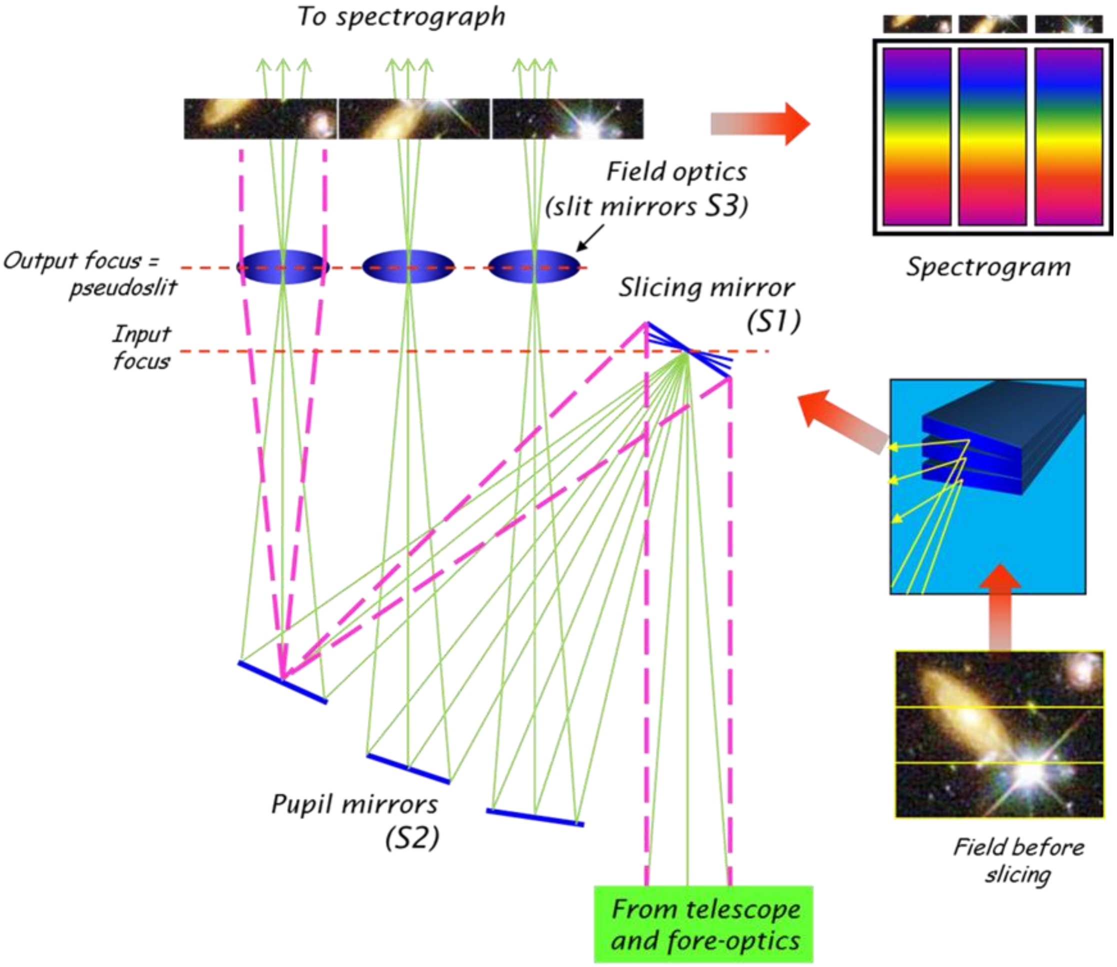


Figure 1. Basic principle of the Advanced Image Slicer.

A modification to the Advanced Image Slicer design was developed by the then Edinburg Observatory[14]. They reasoned that only 2 mirrors are necessary to reimage the field and the pupil so 2 mirror arrays should be enough, not 3. They then removed the slit mirror array and replaced it by 2 long rectangular mirrors, and modified the curvature of the other optics accordingly. This simplifies the mechanical design and in principle reduces the cost but it brings some problems. First, it degrades the field and pupil image qualities; second, it is impossible to have a unique linear slit, the slit needs to be "staggered." Figure 2 shows the result. Apart from reducing the length of the spectra, it worsens cross-contamination because bright lines as OH lines can contaminate a region of faint lines in an adjacent slice image. A possibly more important disadvantage that may cancel the cost reduction is that it makes alignment more difficult. Manufacturers have brought this point to us. For MAVIS, it can be a serious problem because angular precision is exacerbated by the near diffraction limit design which asks for particularly high angular precision.

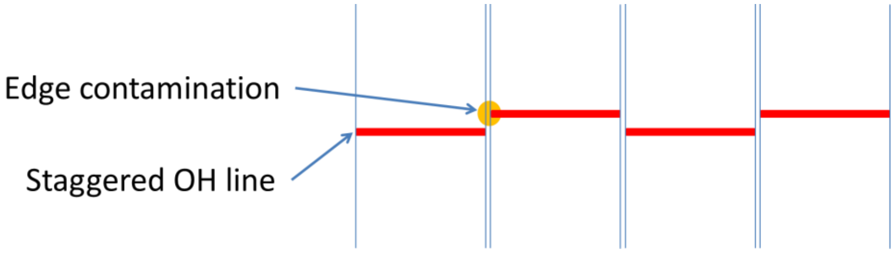


Figure 2. Sketch of the effect of a staggered slit in the version of the AIS developed by the then Edinburg Observatory. It represents the spectra from 4 slices where a bright OH line contaminates adjacent regions where faint lines can be present.

There is a third option that we are developing, one that keeps some of the advantages of the Edinburg version of the AIS while removing the staggered slit. There is again a slit mirror array but one that is of much lower cost because it is made of 2 staggered flat mirrors. The staggered slit is then replaced by a linear slit as in the standard design of the AIS. The field and pupil image degradation still remains however as the increased difficulty of doing the alignments. Figure 3 shows a sketch of the design. The 2 staggered mirrors are interleaved to create a simple slit mirror array. The 3 options are nevertheless under study. For the preliminary design, both the staggered slit and staggered mirrors options were studied. Since there is not much difference between the 2 from an optical point of view, we present the staggered slit option in this paper.

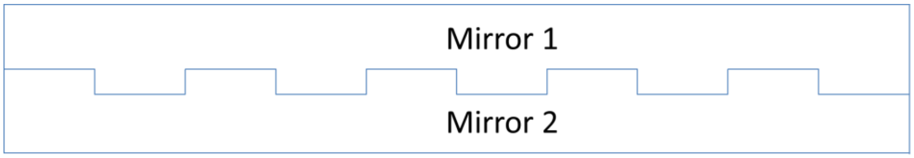


Figure 3. Layout of staggered mirrors creating a slit mirror array.

Figure 4 shows the full preliminary design for 50 mas spaxels for 3 slices: top, middle and bottom of the slicing mirror. Reflective fore-optics are used (section 3). The light comes from the pickoff mirror after the AO system that selects which mode is used, spectrograph or imager. The field splitter then sends the light from half the field to the fore-optics in each of the 2 arms and an image is formed on each slicing mirror. It contains 50 slices 0.05" x 7.2" in this configuration so the total field on the field splitter is 5" x 7.2". The slice mirrors direct their beam each to a reimaging mirror. In this type of design, one line of mirrors would cause some vignetting so 2 lines of 25 mirrors are needed. Each mirror reimages a slice image on the slit where are 2 flat mirrors. Each of these 2 receives the light from one of the 2 lines of reimaging mirrors. All the 50 beams must point toward the centre of the spectrograph input pupil so the 2 flat mirrors must have slightly different angles since the incident angles from the 2 lines of reimaging mirrors are different.

Figure 5 shows a top view from the slicing mirror to the slit. The reimaging mirrors demagnify the slice images to feed an F/10 spectrograph in each arm. While the nominal beam is F/20 in the spectral direction, there is focal ratio degradation by diffraction and pupil aberrations so the spectrograph is also F/10 in that direction to capture more light. More precise calculations will be needed to determine the optimum unvignetted shape of the beam in the spectrograph.

The incident angle on the slit mirrors from the extreme reimaging mirrors is not the same than in the centre because they must aim at the centre of the spectrograph pupil after reflection.

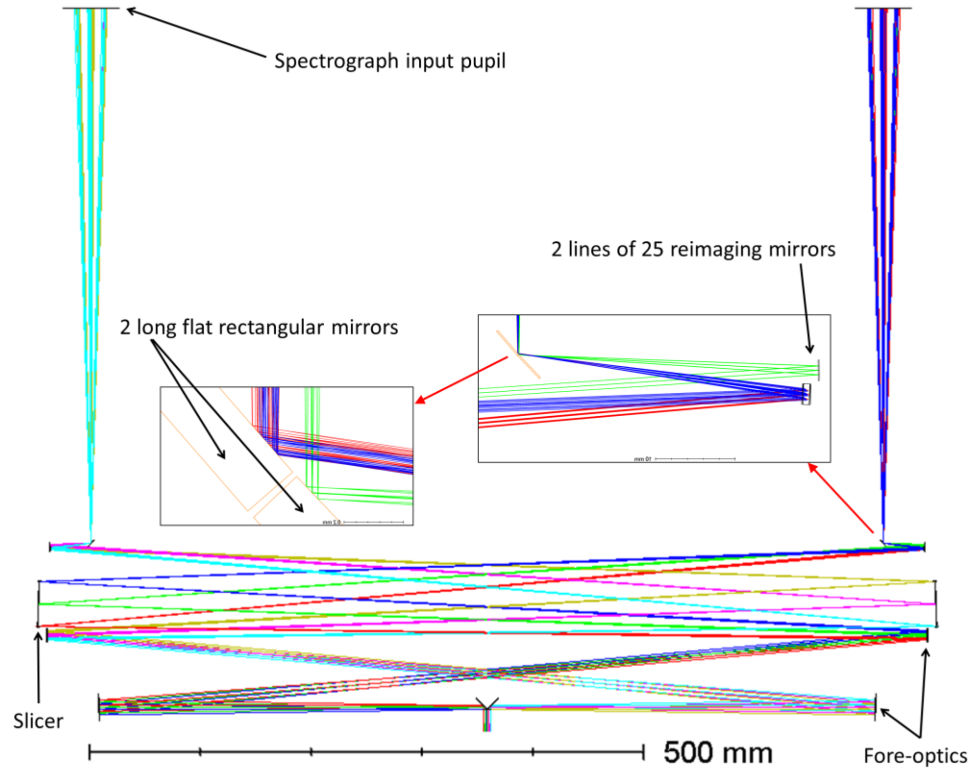
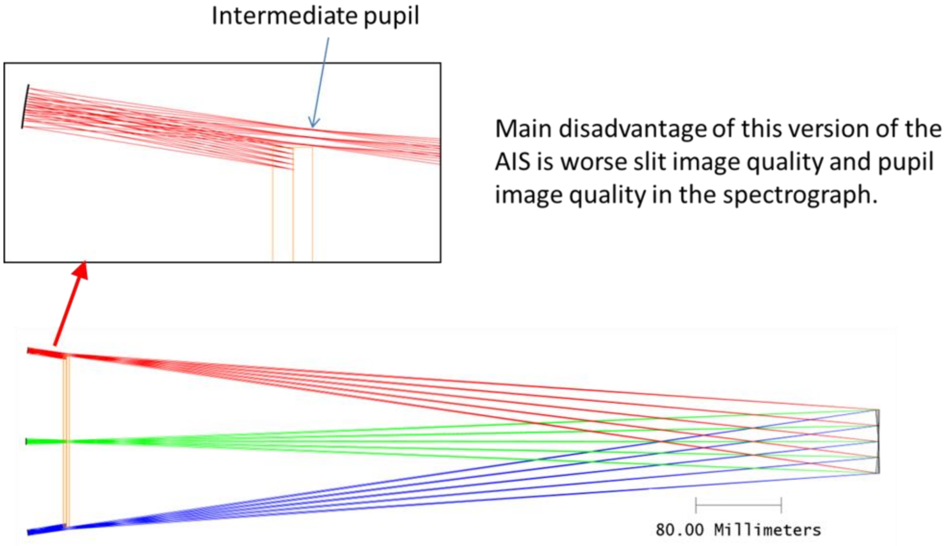


Figure 4. Preliminary design of the MAVIS IFU for 50 mas spaxels and reflective fore-optics. The slit option chosen is that with 2 flat mirrors on the slit. The rays of 3 slices are shown in each of the 2 arms: top, middle and bottom of each slicer. The inputs of the 2 spectrograph are shown.



Main disadvantage of this version of the AIS is worse slit image quality and pupil image quality in the spectrograph.

Figure 5. Top view of one arm of the preliminary design from the slicing mirror to the slit. The 2 long flat rectangular mirrors are almost on the focal plane of the slit.

### 2.1 Image quality

The as-designed image quality delivered by the fore-optics on the slicer is so good that it is negligible. The PSF has a Gaussian Equivalent FWHM of 1.5 mas. The image quality of the slit is not as good but still fine. Figure 6 shows the PSF from the worst slice image. The main aberrations are astigmatism and defocus. While acceptable, the PSF image quality can be improved.

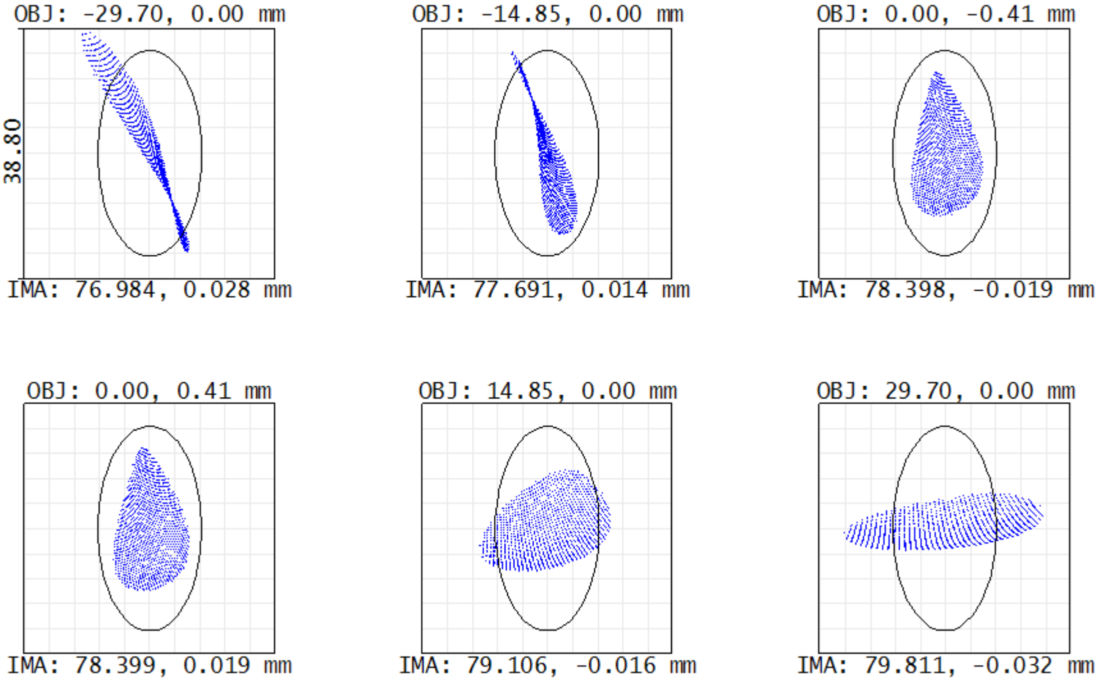


Figure 6. Image quality on the slit of the worst slice of the preliminary design. The boxes are 2 pixel wide. The ellipses are the first diffraction minimum of the central wavelength.

## 3. FORE-OPTICS

The fore-optics start with the system that selects the spectrograph mode or the imager mode which is a pickoff mirror that will send the light toward the IFU in spectrograph mode. It is followed by a system that splits the field in 2 and sends the light toward the 2 arms of the IFU. It is therefore called the field splitter. Then follows in each arm optics that reimage the subfield on the slicing mirror with the correct magnification. These are the arm fore-optics. Reflective and transmissive optics were studied. Since there are two requested spaxel sizes, 25 mas and 50 mas, the magnification will be different for each of them. A different set of arm fore-optics must then be used. The 2 set will be on a motorized slide that permits to select one or the other.

### 3.1 Selection of spectrograph mode

MAVIS has an imaging and a spectroscopy mode. A system must be in place to choose one or the other. This is done with a pickoff mirror. In the first design, the mirror would rotate 90° to send the light to the imager or the spectrograph. In the latest design however, the imager was removed and directly integrated into the optics of the AO system. While a rotating pickoff mirror can still be used to send the light to the imaging detector or the spectrograph, there is a more interesting possibility under study: the use of the imager and spectrograph simultaneously. Figure 7 shows a possible design to do so. The pickoff mirror now does not rotate but is inserted instead. In imaging mode, the pickoff mirror is at its parking position on the right. The detector is then fully used for imaging. In spectrograph mode, the pickoff is inserted in front of the detector so that the input of the IFU is now fully illuminated. However, the field of the IFU is much smaller than the field of the detector and the beam is extremely slow. It is then possible to fully illuminate the IFU without vignetting while illuminating most of the imaging detector. The pickoff mirror must however not be too far from the detector; otherwise the beam size would force to block most of the light toward the detector. In the present design, the beam is f/53 and the IFU is 5" x 7.2" in its largest configuration while the detector is 30" x 30". Most of the detector is then not masked by the pickoff mirror.

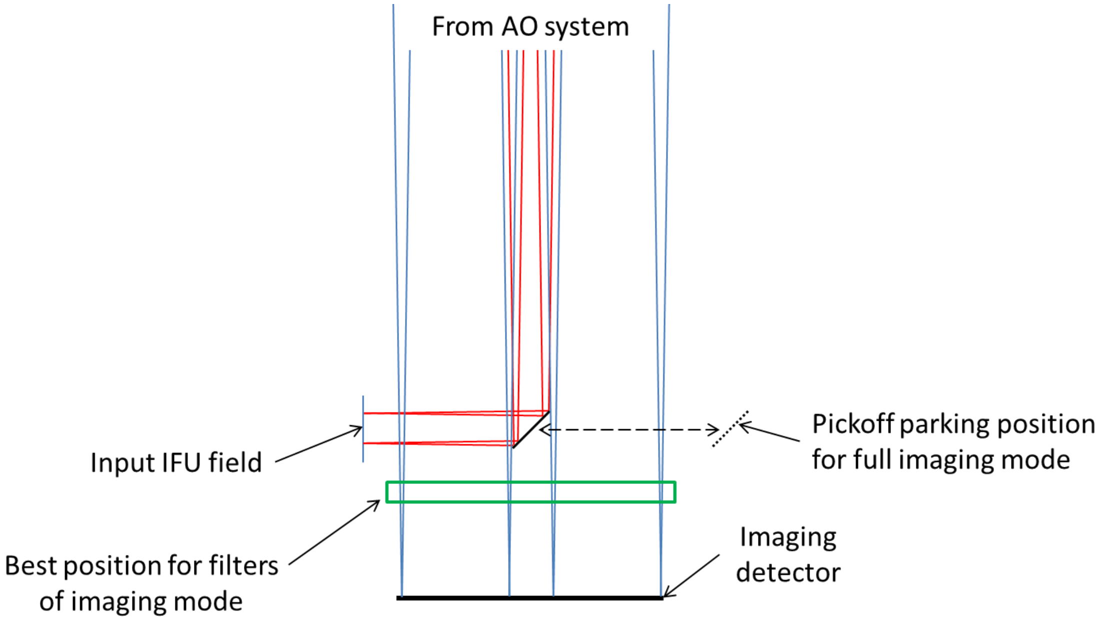


Figure 7. System for the selection of the imaging or spectrograph mode (here in spectrograph mode position). Even in this mode, most of the imaging field can be viewed.

One limitation to this system is the position of the filters of the imaging mode. To avoid filtering the light going to the spectrograph, they must be placed after the pickoff. This may impose some restriction on the distance between the pickoff mirror and the detector, forcing it to be further away from the detector so vignetting more than it would at its optimum position. It is however difficult to imagine that the imaging mode cannot at all be used at the same time than the spectrograph mode.

### 3.2 Reflective fore-optics

While the optics that chooses which mode is used is a reflective mirror, the rest of the fore-optics can be reflective or transmissive. If reflective, the field splitter will be a V-mirror (Figure 8) with its edge right in the focal plane. The sharper the edge, the less light is lost at the junction between the 2 subfields. Then follow in each arm 2 mirrors that reimage the input subfield on the slicing mirror. As explained in section 2, the arm fore-optics magnify 2 times more in the spectral direction than in the direction along the slice which is the spatial direction in the spectrograph. The 2 mirrors must be toroidal to achieve this. The curvature in each direction is independent of the curvature in the other. Figure 8 shows the arm fore-optics for 25 mas and 50 mas. The distances between mirrors are not the same to achieve the correct magnification without changing the position of the input field and the slicing mirror, and get the best image quality.

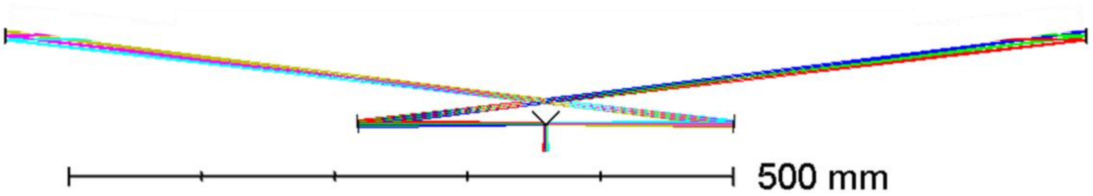


Figure 8. Reflective fore-optics for the 25 mas spaxel size. The 50 mas fore-optics can be seen in Figure 4.

### 3.3 Transmissive fore-optics

A critical problem with the reflective optics of MAVIS is that it is difficult to have good reflection coatings for the wavelength range from 370 nm to 930 nm. Enhanced silver coatings do not have good reflectivity at wavelengths < 400 nm unless their average at all wavelengths is quite low while dielectric coatings have so much layers that uncertainties in their thickness create spikes of low reflectivity in the reflection curve if they are to give a high average reflectivity. Transmissive optics may reduce that problem but good transmission coatings are then necessary and the number of glass-air surfaces must be minimized. The V-mirror of the field splitter was replaced by 2 touching total internal reflection prisms and toroidal lenses replace the toroidal mirrors. However, chromatic aberrations make it necessary to have more optics, minimum 3 lenses instead of the 2 mirrors. This would give 8 glass-air surfaces when including the field splitter instead of the 3 for the reflective optics. It is however possible to insert it in the arm fore-optics to remove 2 surfaces as was done in the design of Figure 9. The field splitter is now part of one of the lenses. The focal plane is now inside the glass with its middle point right on the junction between the 2 total internal reflection prisms. A complication compared to the mirror design is that the optics before the focal plane illuminate the whole field while the mirror optics are reimaging only the subfield. These optics are then centered on the optical axis of the full field, not the subfield. All optics are spherical except the last lens in each arm which is toroidal on both sides. It is this lens that creates the larger magnification in the spectral direction. Its 2 surfaces behave as 2 lenses at a distance determined by its unusually large thickness. The image and pupil image qualities are not as good as for the mirror design. More lenses can be added but at a price of more surfaces each reducing the transmission. The choice is then not clear between mirror and lens designs and how many lenses to use in the latter. All aspects must be carefully evaluated.

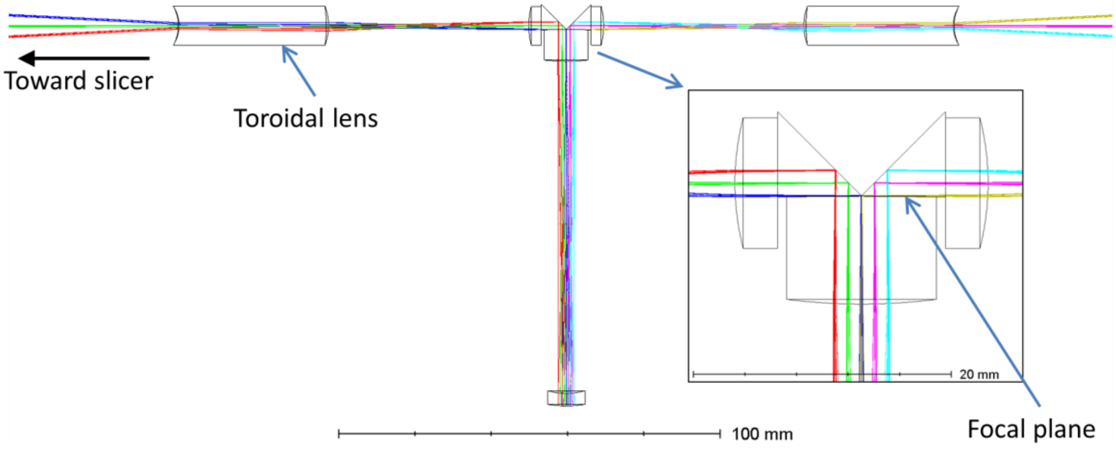


Figure 9. Transmissive fore-optics including the field splitter for 25 mas spaxels.

## 4. EXIT PUPIL OF THE IFU

The exit pupil of the IFU is the entrance pupil of the spectrograph. All the exit pupils of the optical systems, each for a slice, form together the exit pupil of the IFU. It has an elliptical shape because the magnification in the spectral direction is twice that in the spatial direction of the slit. As explained previously, this is done to have a square spaxel on the sky while having also a proper sampling of 2 pixels on the detector in the spectral direction. Due to the conservation of the A.Omega product, the nominal pupil is then 2 times smaller in the spectral direction than in the spatial. The pupil size is also different for the 2 spaxel size of 25 mas and 50 mas. The magnification is twice for the 25 mas spaxel than for the 50 mas. The conservation of the A.Omega product then tells us that the 25 mas pupil will be 2 times smaller than the 50 mas pupil in both directions. The design was then made for the 50 mas pupil, IFU and spectrograph, since it is the largest. The as-designed pupil is affected by 2 types of aberrations: the as-designed aberrations and the slice diffraction aberration. Mechanical aberrations as alignments will add to that. Figure 10 shows the pupil of the preliminary design for 3 slices. It gives a good estimate of its size and geometrical aberrations in both directions. The main aberration is a form of astigmatism. It enlarges the pupil in its smallest direction which is not as bad as in the other because focal ratio degradation in the small direction does not fasten the overall focal ratio but it does in the long direction.

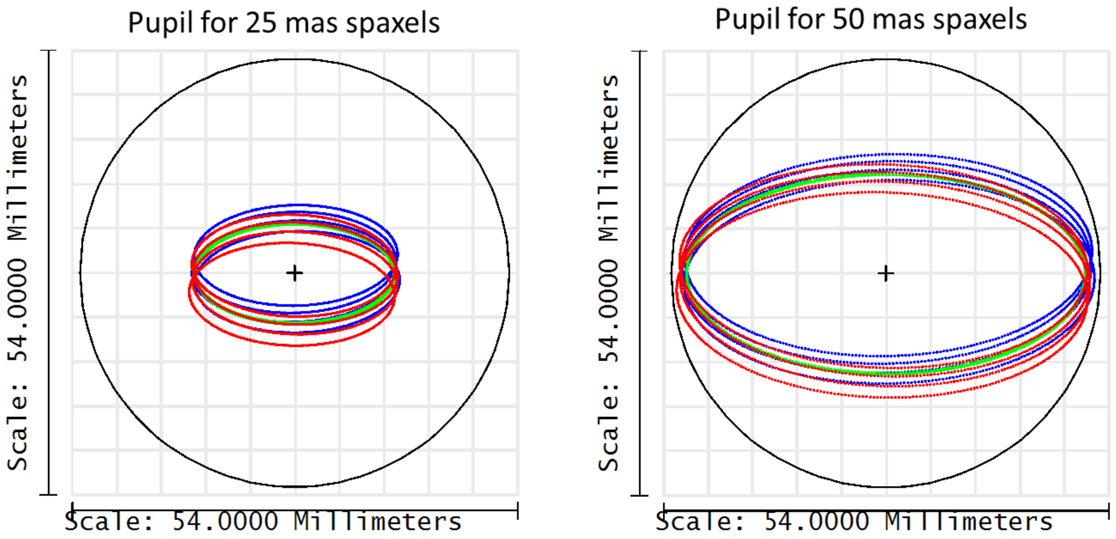


Figure 10. Exit pupil of the IFU for 25 mas spaxels (left) and 50 mas spaxels (right) including geometric aberrations for the preliminary design in Figure 4 so with reflective fore-optics. Red and blue lines are for the extreme slices of the slicing mirror while green lines are for a slice in the centre. Spectral direction is along the vertical.

The second aberration, the slice diffraction, is usually negligible but not here because we are sampling near the diffraction limit. For the longest wavelength of 930 nm and an 8-m telescope, it is 1.22 * λ/D * (206265000 mas/Rad) = 24 mas. This is then not negligible compared to the spaxel size. In the present design, it is the 50 mas spaxel size that matter. The angular diffraction by the slices is in fact the same for both spaxel sizes because the slice width is the same in mm. It is the pupil size that changes. The slice diffraction is then larger with respect to the pupil size for the 25 mas spaxels because the pupil is smaller. Figure 11 shows the slice diffraction focal ratio degradation in the middle of the pupil in the spectral direction for the 50 mas spaxels. The slice diffraction is negligible in the other direction because of the very long length of the slices of 7200 mas. The combination of slice diffraction and geometric aberrations (including mechanical aberrations as alignment) will determine the shape and size of the stop in the spectrograph to minimize vignetting losses.

The slice diffraction caused confusion for the first Advanced Image Slicer on the first GNIRS instrument of Gemini (which was later accidentally destroyed) even if there was then no Adaptive Optics system on the telescope. Astronomers testing the IFU thought that they were doing something wrong because they were getting >100% transmission, up to 142% near 4 µm. When they finally communicated their concern to the first author of the present paper, he reassures them that it was perfectly normal. They compared the transmission with that of a 0.1" slit but the longer the wavelength and the smaller the slit, the more slit diffraction. GNIRS had a stop quite tight with respect to the geometric pupil so there was a lot of diffracted light that was vignetted for that slit. The slice pupil was however 2.3 times smaller in the spectral direction so a lot of the diffracted light went through the circular stop. Slice diffraction is then an important phenomenon to study when designing an image slicer especially for the design of the spectrograph.

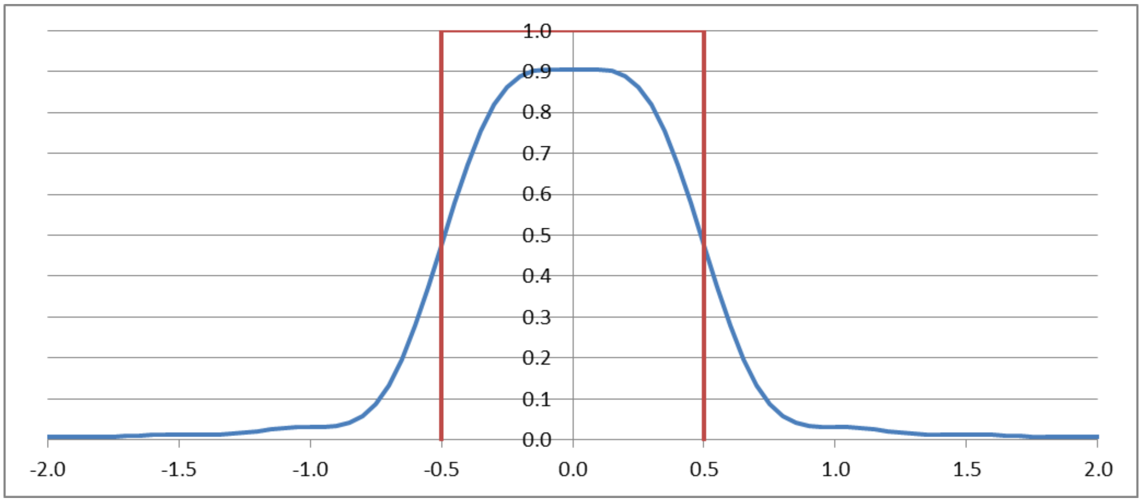


Figure 11. Nominal IFU geometric exit pupil (red) and exit pupil with slice diffraction (blue) for the longest wavelength of 930 nm. The graph shows a cut in the centre of the pupil along the spectral direction.

## 5. CONCLUSION

The preliminary design of the MAVIS IFU demonstrates that a design based on the concept of Advanced Image Slicer can be made with a good image quality on the slicing mirror, the spectrograph slits and the spectrograph entrance pupils. Different options are under study: the pickoff mirror selecting the mode, spectrograph or imager, can be a rotating mirror or a sliding mirror, the latter permitting to use imager and spectrograph at the same time; fore-optics can be reflective or transmissive; the slit optics can be standard AIS slit mirrors, flat rectangular mirrors or staggered mirrors. Other options under study have to do with a trade-off between cost and performances as the use of slice mirrors with identical radius of curvature, the same for the reimaging mirrors, and the use of toroidal mirrors not only for the fore-optics. We intend to study as much as possible of these options before the final design is done.

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