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Image Slicer Design

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SUMMARY

A milestone of WP60.2 for September, 30th, was the design of an image slicer optimized for GRIS, the infrared spectrograph of 1.5 m GREGOR telescope, to make solar observations obtaining the spectra of a 2-D region simultaneously and to validate the concept for the European Solar Telescope instrumentation. This document presents the image slicer layout with an optical quality at diffraction limit.

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LIST OF ABBREVIATIONS

IFU	Integral Field Unit
FoV	Field of View
EST	European Solar Telescope
MuSICa	Multi-Slit Image slicer based on collimator-Camera
GRIS	GREGOR Infrared Spectrograph
IAC	Instituto de Astrofísica de Canarias
IFS	Integral Field Spectroscopy

1. WP60.2 objective: image slicer design

1.1 *OBJECTIVE*

The objective is to develop a prototype of an Integral Field Unit (IFU) based on an image slicer optimized for GRIS, the infrared spectrograph of GREGOR telescope, to make solar observations obtaining the spectra of a 2-D region simultaneously and to validate the concept for the European Solar Telescope instrumentation.

1.2 *INTEGRAL FIELD SPECTROSCOPY*

Integral Field Spectroscopy (IFS) is a technique that provides the spectra of all the points of a bidimensional field of view at the same time and under the same conditions using an integral field unit (IFU). Its application offers information along three dimensions: X, Y, λ. There are different alternatives of Integral Field Units (optical fibers, microlenses and image slicer), however, the optimum option for polarimetric measurements is the image slicer. A new concept of image slicer, called MuSICa (Multi-Slit Image slicer based on collimator-Camera) [1], has been designed specifically for the integral field spectrograph of the 4-m European Solar Telescope (EST) [2] and a prototype has been designed for the GRIS spectrograph [3] at 1.5 m GREGOR solar telescope [4].

The development of this technique is very useful in solar physics, where the magnetic structures evolve in very short time scales and, using standard long-slit spectrographs, these structures can move out of the field of view of the entrance slit in large exposure times. Thus, Solar Integral Field Spectroscopy is a technique in recent development for the largest ground-based [5] and space solar telescopes [6].

1.3 *IMAGE SLICER CONCEPT. MuSICa*

An image slicer is an optical system placed at a focal plane that divides the image into slices and generates the image of each of them which are later distributed generating one or more long-slits. This generated slit feeds a spectrograph as in the case of conventional spectrographs but, since this slit is a reorganization of a bidimensional region, the spectra of all the points of that 2-D field of view are obtained simultaneously.

Image slicers use arrays of mirrors (for pure reflective image slicers) to reflect each part of the image in a different direction using different orientations (tilt X, tilt Y). These orientations are carefully controlled to distribute the images of each 'sliced' part of the field of view into the output slit or slits. Thus, the optical path of each 'sliced' part of the field of view is defined by the reflection using one mirror of each array and generating a piece of the generated output slit, which is known as 'mini-slit'.

MuSICa for GRIS is a 1:1 telecentric system. It is composed by three arrays of mirrors: slicer mirror array, collimator mirror array and camera mirror array. The slicer mirrors are flat, they are located at the telescope image focal plane and each slicer mirror has a different orientation (tilt X, tilt Y) to reflect a part of the entrance field of view and send it to a collimator mirror. The second optical element is the collimator mirror array, composed by eight spherical mirrors. In front of the collimator mirrors the camera mirrors are placed, which are also spherical. Collimator and camera mirrors have antisymmetric correspondences, thus, the intermediate pupil images, generated between them, lie at the same position and are all overlapped. At the pupil position a mask is placed to avoid the contribution of scattered light. The third optical element is the camera mirror array, composed by eight spherical mirrors with the same focal length that the collimator mirrors. The camera mirrors focus the beams generating their images ('mini-slits') at their focal length. The image slicer output slit is composed by the distribution of the eight mini-slits into a long-slit. Collimator and camera mirrors are distributed in two columns whose length is similar to that of the output slit, what reduces the angles and optimize the optical quality. The final slit is generated alternating focusing beams of each one of the two columns of camera mirrors to compensate the angles. The pupil images are overlapped in an intermediate plane between the slicer mirror array and the generated slit.

1.4 REQUIREMENTS AND SPECIFICATIONS

GRIS [5], the GREGOR infrared spectrograph, is a long slit spectrograph that operates in the near-infrared, from 1 to 2.3 μm with very high resolution (R~500,000) for measurements of the photospheric and chromospheric magnetic field. It presents a Czerny-Turner layout using off-axis parabolic mirrors with a focal length of 6 meters, a focal-ratio F/39.79 and an echelle diffraction grating with 316 grooves/mm and a blaze angle of 63.4º. The current image scale of GREGOR telescope is 3.5 arcsec/mm and the focal-ratio is F/39.79. The telescope effective focal length is 58932.86 mm. The detector of GRIS spectrograph has 1024 x 1024 pixels with a pixel size of 18 μm. The image slicer and the spectrograph are 1:1 systems and there is a focal reducer 2:1 before the detector.

TELESCOPE PARAMETERS	
Image scale	3.5 arcsec/mm
Effective focal length	58932.86 mm
Focal-ratio	F/39.79

Table 1. Main parameters of the GREGOR telescope.

The IFU field of view is 21.08 arcsec^2, 2.8 arcsec height equivalent to 0.8 mm (eight slicer mirrors of 100 μm width) and 7.53 arcsec length. The image slicer generates a slit for the polarimetric mode of observation with 60.228 arcsec length by 0.35 arcsec width. This slit is composed by eight mini-slits and seven spaces of 10 pixels between the mini-slits. If only the useful field of view is considered, then the entrance IFU field of view is 17.993 arcsec^2, 6.426 arcsec length by 2.8 arcsec height. The dimensions of the output slit are 17.208 mm length by 0.1 mm width. The IFU will be coupled to the TIP-II polarimeter and, since the generated slit corresponds to the spectro-polarimetric mode of observation, the slit will be duplicated in its two orthogonal linear polarizations illuminating the spectrograph with a slit twice larger and using a half of the detector for each polarization mode. The design should be telecentric with the pupils of the image slicer associated to different sliced parts of the entrance field of view, overlapped over the spectrograph diffraction grating. To distinguish the spectra associated to each mini-slit, these mini-slits have to be separated between them. The separation in height of the mini-slits between the beams of the top and bottom rows of the camera mirrors can be the order of 1 or 2 mm and the separation in width is 10 pixels, what means 360 μm at the IFU image focal plane and 180 μm in the detector. The specifications and requirements for the IFU prototype are presented in Table 2.

SPECIFICATIONS AND REQUIREMENTS FOR THE IFU PROTOTYPE	
Input focal-ratio	F/39.79
Output focal-ratio	F/39.79
FoV	21.08 arcsec^2 *
Number of slices	8
Slices width	100 μm
Number of output slits	1
Generated slit field of view	60.228 arcsec x 0.35 arcsec= 21.08arcsec^2
Generated slit dimensions	17.208 mm x 0.1 mm
Mini-slits field of view	6.426 arcsec x 0.35 arcsec = 2.25 arcsec^2
Mini-slits dimensions	1.836 mm x 0.1 mm
Slicer mirror field of view	6.426 arcsec x 0.35 arcsec = 2.25 arcsec^2
Slicer mirror dimensions	1.836 mm x 0.1 mm
Optimum illumination	telecentric

Table 2. Specifications and requirements for the IFU prototype design. * This field of view considers the size of the generated slit for the polarimetric mode of observation, which is composed by eight mini-slits and seven spaces of 10 pixels between them If only the useful field of view is considered, this means to consider only the field of view of the eight mini-slits without the spaces, then the entrance IFU field of view is 17.993 arcsec^2, 6.426 arcsec length by 2.8 arcsec height.

1.5 DESIGN PARAMETERS

Each array of the image slicer prototype is composed by eight mirrors. Slicer mirrors are flat and the dimensions of each one of them are 0.1 mm width x 1.836 mm length. Thus, the size of the slicer mirror array is 0.8 mm width x 1.836 mm length. Collimator and camera mirrors are spherical with a focal length of 100 mm and their shape is rectangular, with a size of 5.5 mm width x 3 mm height. The pupil mask has only one circular aperture with a diameter of 3 mm in which all the pupil images are overlapped. These technical parameters are shown in Table 3.

TECHNICAL CHARACTERISTICS OF THE IMAGE SLICER PROTOTYPE OPTICAL COMPONENTS	
SLICER MIRROR ARRAY	
Size	0.8 mm width x 1.836 mm length
Curvature	Flat
Size of each mirror	0.1 mm width x 1.836 mm length
COLLIMATOR MIRROR ARRAY	
Size	5.5 mm width x 3 mm height
Curvature	Spherical
Distribution	2 rows of 4 mirrors
Focal length	100 mm
PUPIL MASK	
Number of apertures	1
Aperture Diameter	3 mm
CAMERA MIRROR ARRAY	
Size	5.5 mm width x 3 mm height
Curvature	Spherical
Distribution	2 rows of 4 mirrors
Focal length	100 mm

Table 3. Technical characteristics of the IFU prototype optical components.

1.6 OPTICAL LAYOUT AND OPTICAL QUALITY

After designing different alternatives, the final layout is an image slicer distributed in a vertical plane (see Figure 1) with an optical quality at diffraction limit (Figure 3). A flat mirror is used between camera mirrors and the output slit to drive the image slicer output beam to the spectrograph entrance (Figure 2).

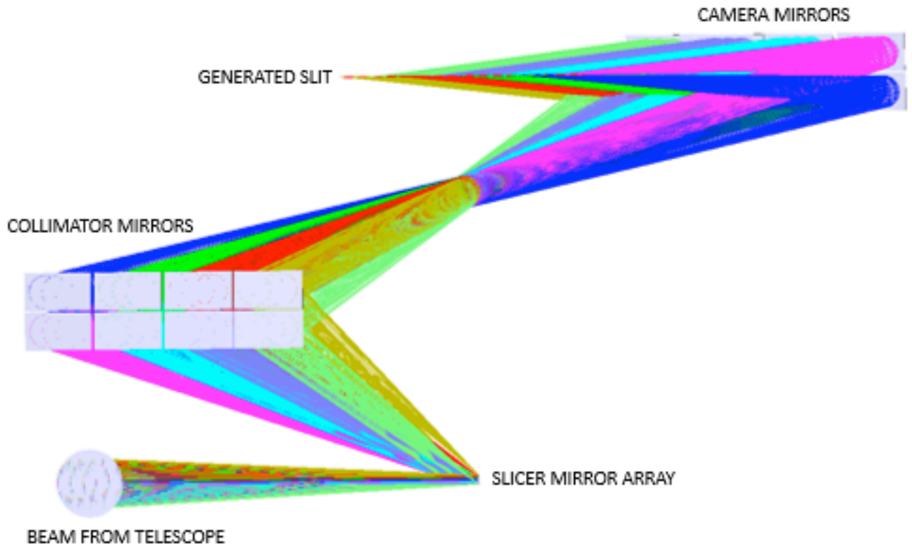

Figure 1. Layout of the image slicer in a vertical plane. The final layout is based on this concept, however, some design parameters can be modified to satisfy all the requirements.

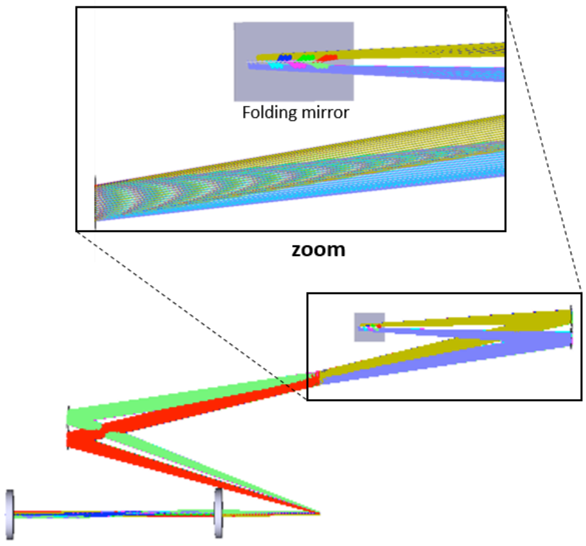

Figure 2. Image slicer layout using a folding mirror to drive the generated slit to the spectrograph entrance. A doublet of lenses has been used in this layout to generate a beam with the telescope focal-ratio.

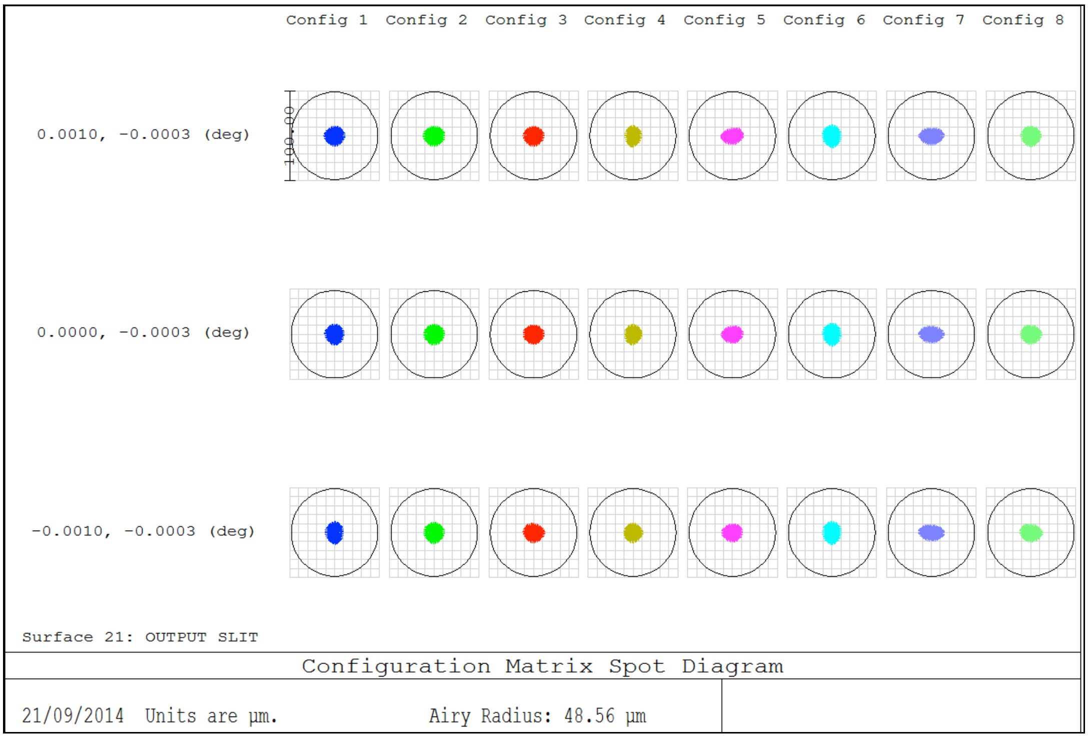

Figure 3. Spot diagram of the optical design showed in Figure 1 in which the beams are all contained within the Airy disk demonstrating that the optical quality of the design is limited by diffraction. This spot diagram has been evaluated at 1 µm.

2. OTHER STUDIES

As well as the optical design, other studies have been carried out for the image slicer, as: the thermal analysis, the diffraction effect analysis, an estimation of cross-talk between slicer mirrors, telecentricity, a preliminary stray light analysis and a throughput budget. In parallel, the coupling of the image slicer to the other subsystems at GRIS spectrograph has also been studied.

According to the thermal analysis done using ZEMAX, since the image slicer is going to be fabricated in zerodur and it will be placed in a room with temperature control, it is not expected any significant effect due to temperature that could deteriorate the instrument performance.

From the preliminary stray light analysis some conclusions have been inferred, such as at least a pupil mask will be used to reduce stray light contribution and, using a second mask, a field mask in this case, located at the slit generated by the IFU, the scattered light contribution is considerably reduced. The pupil mask is important to allow the pass associated to the pupil images in the image slicer and block the rest, especially in the

MuSICa layout which has the camera mirrors in front of the collimator mirrors what could produce multiple undesired reflections reinjected backward.

Diffraction effects have been studied applying ‘Physical Optics Propagation’ (POP) tool of ZEMAX. The PSF diameter, evaluated at 1 μm, is 97.09 μm. Since the slicer mirrors width is 100 μm, at least the 83.3% of the energy is contained within the slicer mirrors (see Figure 4).

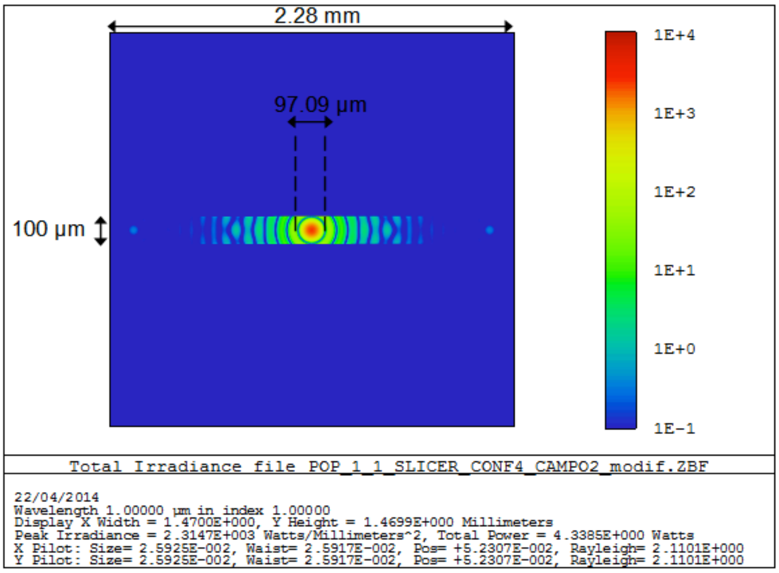

Figure 4. ZEMAX physical optics propagation analysis of a defined pupil at a slicer mirror represented in a logarithmic scale. The slicer mirror width is 100 μm and, as shown in the figure, the PSF, evaluated at 1 μm, has a diameter is of 97.09 μm and, at least the 83.3% of the energy is contained within the slicer mirror.

On the other hand, since there is a fraction of the diffraction pattern that is not contained within the own slicer mirror, there is a ‘cross-talk’ between slicer mirrors. Cross-talk analysis allows to quantify the contribution of light originally assigned to a slicer mirror that affects the others. Figure 5 shows the PSF (left) and the portion of it that is contained within the slicer mirror (right). The first Airy disk is contained within the slicer mirror of 100 μm and there is a fraction of energy (≤16.7%) that can be the total contribution of cross-talk.

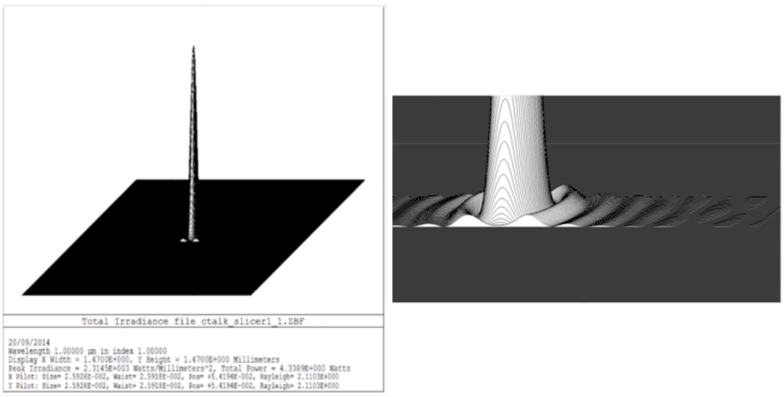

Figure 5. PSF (left) and the portion of it that is contained within the slicer mirror (right).

Table 4 summarizes the cross-talk contributions that have been estimated of slice 1 over the other slicer mirrors of the array and Figure 6 shows a mosaic composed by the portions of the PSF associated to a central field point of slice 1 of the image slicer entrance that affect the other slicer mirrors of the array.

CROSS-TALK CONTRIBUTION OF SLICE 1	
over slicer mirror 2	2.37 %
over slicer mirror 3	0.289 %
over slicer mirror 4	0.0768%
over slicer mirror 5	2.37 %
over slicer mirror 6	0.289 %
over slicer mirror 7	0.0768 %
over slicer mirror 8	0.0227 %
TOTAL	5.4943 %

Table 4. Cross-talk contributions that have been estimated of slice 1 over the other slicer mirrors of the array. The total value is 5.4943 %, thus, the 94.5% of the energy associated to the slice 1 of the field of view is contained within the slicer mirror 1.

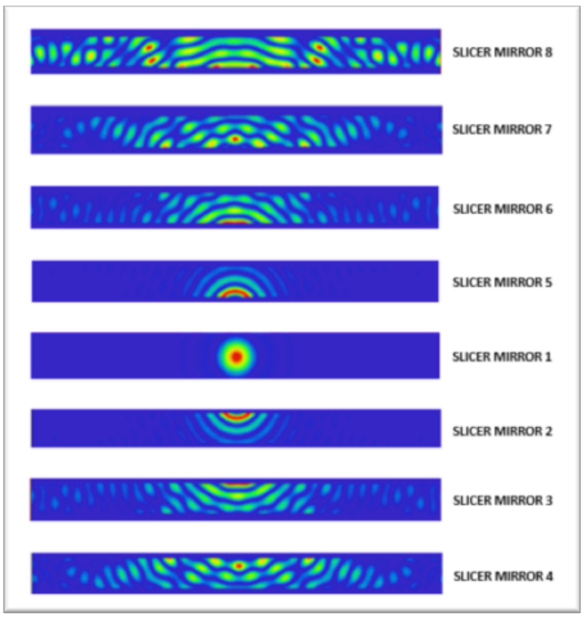

Figure 6. Mosaic composed by the portions of the PSF associated to a central field point of slice 1 of the image slicer entrance that affect the other slicer mirrors of the array.

The throughput budget for the image slicer considering four mirrors with a coating of protected silver is 0.92.

A very important condition in the design of the image slicer is telecentricity and the overlapping of the pupils over the spectrograph diffraction grating. This implies that the mini-slits are not strictly aligned, but in two different heights, each one associated to a row of camera mirrors (see Figure 6). This difference in height is small, the order of 2 mm. The the mini-slits are also separated between them horizontally 10 pixels. This condition has implied changes in the design, such as a reduction of the the focal lengths that are currently 100 mm, what also decreases the size of camera and collimator mirrors. The effective entrance field of view has been modified by two reason: for a slight change in the telescope scale, which is currently 3.5 arcsec/mm (see Table 1) and due to the separation of the mini-slits, for which the size of the slicer mirrors has been reduced.

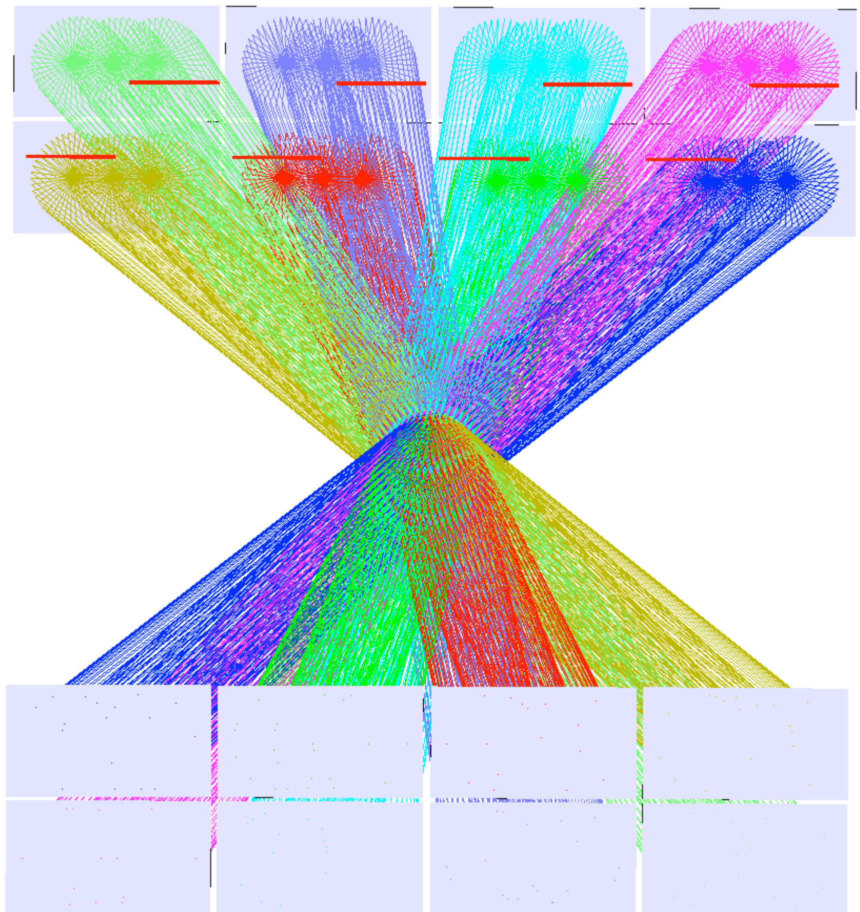

Figure 6. Image slicer layout with the mini-slits separated horizontally and vertically.

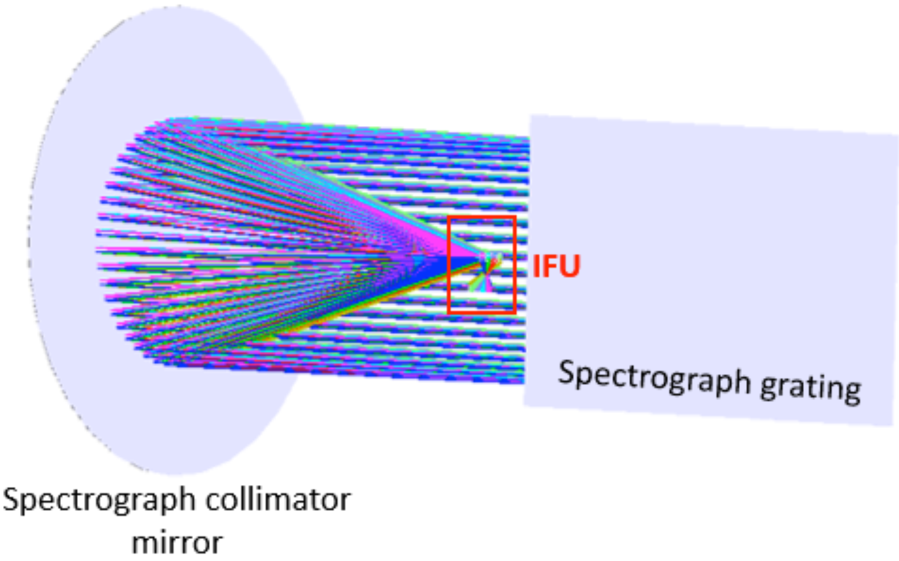

Figure 7. Layout of the coupling between IFU and the spectrograph collimator mirror and diffraction grating.

3. CONCLUSIONS

This document presents the design of the image slicer for GREGOR solar telescope that satisfies the milestone of WP60.2 scheduled for September 30th. The optical design was completed on schedule, as well as other studies carried out for the image slicer, such as: the thermal analysis, the diffraction effect analysis, an estimation of cross-talk between slicer mirrors, telecentricity, a preliminary stray light analysis and a throughput budget. In parallel, the coupling of the image slicer to the other subsystems at GRIS spectrograph has also been studied.

The image slicer design presents an optical quality limited by diffraction with excellent optical performance. Telecentricity is a top level requirement that has implied modifications in the layout, as a reduction of the focal lengths and, thus, in the size of camera and collimator mirrors to generate mini-slits with a minimum separation between them in which the associated chief rays are parallel what allow to overlap the pupils over the spectrograph diffraction grating.

The effective entrance field of view has been modified by two reason: for a slight change in the telescope scale, which is currently 3.5 arcsec/mm and due to the separation of the mini-slits, for which the size of the slicer mirrors has been reduced.

4. REFERENCES

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ANNEXES

A. LIST OF REFERENCE DOCUMENTS
