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Exploring the application of image slicers for the EUV for the next generation of solar space missions

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ABSTRACT

The Sun is a privileged place to study particle acceleration, a fundamental astrophysical problem throughout the universe. The Extreme Ultra-Violet (EUV) contains a number of narrow emission lines formed in all layers of the solar atmosphere whose profiles allow the measurement of plasma properties like density and temperature, along with the presence of non-Maxwellian particle distributions to be diagnosed. The only way to observe is from space, since EUV radiation is absorbed by the Earth's atmosphere.
Integral Field Spectroscopy combined with polarimetry is key for the study of the Sun, but the current EUV technology is limiting: the transmission of optical fibres IFUs (Integral Field Units) is low and in-flight effects affect polarisation measurements. The best solution seems to be image slicers. However, this technology has not yet been developed for the EUV spectral range. This communication explores a new highly efficient and compact integral field spectrograph layout based on the application of image slicers combining the surfaces of the IFU with those of the spectrograph, suitable for space applications.

Keywords: EUV Spectroscopy, Integral Field Spectrographs, image slicers, solar instrumentation, space instrumentation

1. INTRODUCTION

Among the 400,000 million stars of the Milky Way, the Sun, a small G2V star, hosts our planetary system. With an inner activity dominated by its magnetic field, many of the phenomena that take place within it are still poorly understood. The development of two 4-m aperture ground-based telescopes: DKIST[1], which saw first-light in 2020, and the European Solar Telescope[2] (EST), currently in the design phase, will provide crucial advances, and both include/will include advanced instrumentation. EST is optimised for the study of the solar photosphere and chromosphere, while DKIST is optimised for the study of the corona. Together they cover a spectral range extended from the visible to the infrared allowing them to address many open questions regarding the emergence and evolution of the solar magnetic field.

The Sun is also a privileged place to study particle acceleration, a fundamental astrophysical problem throughout the universe. The Extreme Ultra-Violet (EUV) contains many narrow emission lines formed in the upper layers of the solar atmosphere whose profiles allow the measurement of plasma properties like density and temperature, along with the presence of non-Maxwellian particle distributions to be diagnosed. At these short wavelengths, the only way to observe is from space, since EUV radiation is absorbed by the Earth's atmosphere. Particle acceleration is a fundamental process arising in many astrophysical objects including active galactic nuclei, black holes, neutron stars, gamma ray bursts, accretion disks, solar and stellar coronae and planetary magnetospheres. Its ubiquity means that energetic particles fill the Universe and influence the conditions for the emergence and continuation of life. In our solar system, the Sun is the most energetic particle accelerator and its proximity makes it a unique laboratory in which to understand astrophysical particle acceleration.

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Instrumentation for EUV spectroscopy already exists. An example is the slit spectrograph EIS[3], whose 1D spatial field of view requires a slow scanning across an active region, taking five to ten minutes, to build up a spatial 2D picture of the Sun. In order to study rapidly evolving processes, such as flares, and the accompanying magnetic field changes, observing the entire 2-D field of view and obtaining the spectra of all its points simultaneously (without scanning) is highly desirable. This is possible through the application of Integral Field Spectroscopy, also known as IFS or 3D Spectroscopy, since the output is a datacube with information along three dimensions, two spatial: X,Y, and the spectral one, λ.

2. IFS FOR THE EXTREME ULTRA-VIOLET USING IMAGE SLICERS

Integral field spectrographs are composed of two subsystems: a field reformatter, also known as Integral Field Unit or IFU and the spectrograph. The IFU reorganises the entrance 2-D field of view into one or more slits that illuminate the spectrograph. Thus, integral field spectrographs also have an entrance slit, as in the case of long slit spectrographs, but now this slit has information of the bidimensional field of view. The spectrograph disperses the incoming light and focuses the spectra on the detector. Within the IFU alternatives, optical fibres were discarded due to their low transmission in the EUV. Our proposal is the application of image slicers.

An image slicer is an optical system composed of different arrays of mirrors, where each one of those mirrors presents a different orientation (tilt around the X and Y axes). The most important component is the slicer mirror array located at the telescope image focal plane. Due to the different orientation of each slicer mirrors, each one of them reflects a slice of the field of view (FOV) towards a different direction. The effect obtained is that of a sliced field of view, as shown in Figure **1**. The other arrays of mirrors control the intermediate and exit pupil positions and focus the image of the slices on top of each other, generating the spectrograph entrance slit or slits. The substrate for the slicer mirrors can be metallic, such as Aluminium, or glass, such as Zerodur or Fused Silica, which will later be coated to be used in reflection. A sketch of the image slicer concept is shown in Figure **2**, where the entrance field of view is divided in three slices and the spectrograph slit is composed of the aligned images of the slices.

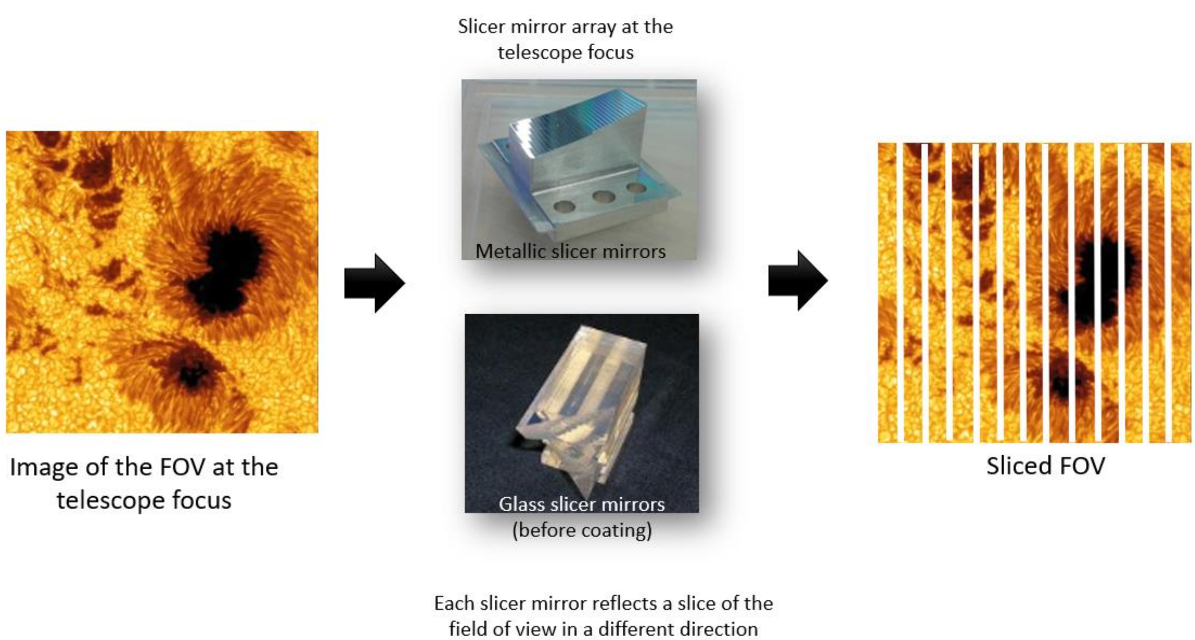

Figure 1. Sketch showing the concept of the sliced field of view (FOV) generated by the slicer mirror array at the telescope focus. The substrate for the slicer mirrors can be metal or glass as shown in this picture. In this example, the metallic slicer mirror array was manufactured at Durham University and the glass slicer mirror array, shown before depositing the coating, was manufactured by Winlight Optics, currently Bertin Winlight.

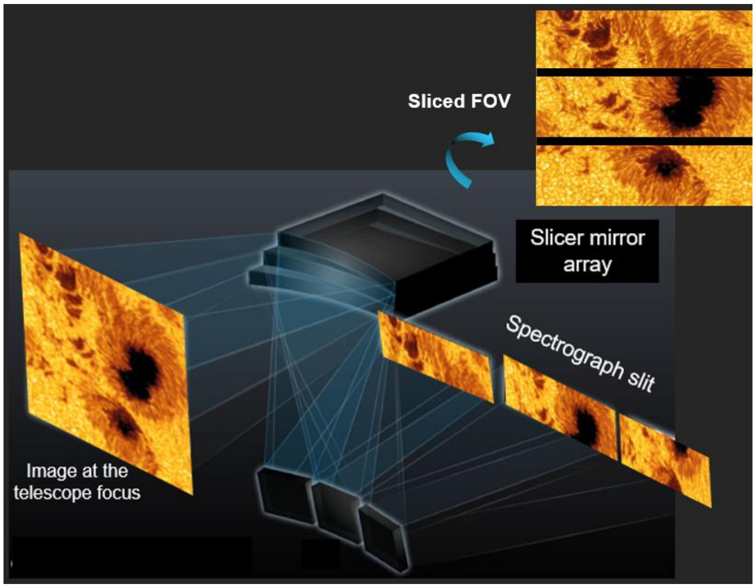

Figure 2. Sketch of an image slicer dividing the field of view in three slices to show the concept.

Image slicers present the following functionalities and characteristics:

- They reorganise a 2D field of view into one or more slits to illuminate the spectrograph.
- They define the entrance slit dimensions (width and length).
- They define the sampling, directly linked to the spatial resolution.
- They impact the spectral resolving power of the spectrograph, related to the spectrograph slit width.
- They generate an intermediate pupil image and control the position of the exit pupil, especially important for telecentric systems.
- They can produce a magnification using the image slicer components without needing any additional optical surfaces.
- They allow the perfect coupling between telescope and spectrograph without light losses.
- There is no focal-ratio degradation or polarization effects as in the case of using optical fibres.
- They are highly efficient. The coating is selected to optimise throughput in the spectral range of interest.
- They are very compact, making them perfect for space instrumentation or updates of existing long slit spectrographs or integral field spectrograph proposals with space limitations.

Although integral field spectrographs using image slicers in the EUV are not yet available, this technology benefits from ground-based and space heritage, for different spectral ranges and different applications. For solar ground-based instrumentation, image slicers were first proposed for the integral field spectrograph[4] of the European Solar Telescope, with a multi-slit image slicer called MuSICa[5]. The GRIS[6] spectrograph at GREGOR solar telescope was upgraded from a long-slit spectrograph to an integral field spectrograph using an image slicer[7] which has been operating for several years. For night-time astronomy, image slicers have been used for decades, for different spectral ranges covering from very short wavelengths, like the two image slicers of CUBES[8,9] for VLT, to the infrared, for example, the image slicers of GNIRS[10] at the Gemini North telescope. There are image slicers already in space on-board the James Webb Space Telescope, in MIRI[11] and NIRSpec[12], already demonstrating remarkable performance. The success of the image slicer technology at other wavelengths supports the feasibility for the EUV, whose development can be highly beneficial for future space missions.

3. SISA AS PART OF THE SPARK PAYLOAD

In response to the ESA's call for an M-class mission opportunity 2022, a proposal called SPARK (Solar Particle Acceleration Radiation and Kinetics), led by Dr. Hamish Reid from UCL was submitted. The SPARK mission presents a powerful combination of γ-ray, X-ray and EUV imaging and spectroscopy at high spectral, spatial and temporal resolutions. SPARK's unique combination of cutting-edge capabilities makes it ideally suited to address open questions regarding particle acceleration in the solar corona and the evolution of solar eruptive events. SPARK was selected in Phase 1 and the Phase 2 proposal has been submitted recently. If selected, SPARK's scheduled launch in 2036 is aligned with the expected peak of the solar cycle, when many solar eruptive events are expected to occur. SPARK deploys a suite of three instruments, one of them is an integral field spectrograph using image slicers, SISA.

3.1 Specifications

SISA (**S**pectral **I**maging of the **S**olar **A**tmosphere) will be the first integral field spectrograph using image slicers for the EUV. It will provide the simultaneous spectra of a bi-dimensional field of view of 100 arcseconds by 250 arcseconds in two spectral windows at the same time, centred around 18.5nm and 25nm, with 1 arcsecond spatial resolution and a spectral resolving power of R∼3,560 for the shortest wavelengths and R∼5,160 for the longest ones. The specifications are presented in Table **1**.

Table 1. SISA specifications.

SISA Parameter	Performance Requirement	Expected Performance
Spectral Window 1	178–184 Å	178–184 Å
Spectral Window 2	246–258 Å	221–264 Å
Spectral Resolution	0.05 Å FWHM	0.05 Å FWHM
Spectral Resolving Power (R)	3560–5160	3560–5160
Field of View	100”×100”	100”×250”
Spatial Resolution	< 3”	1” in 2 pixels
Temporal Resolution (high signal)	< 3 s	1 s
Temporal Resolution (low signal)	< 30 s	10 s

3.2 Conceptual layout

Although the number of components of an image slicer depends on the design and the specifications, this number is typically two or three. The spectrograph is composed of a minimum of at least three components: the collimator, the grating and the camera. Thus, a typical integral field spectrograph will present at least six optical surfaces. In terms of efficiency, this number of surfaces would be prohibitive in the Extreme Ultra-Violet. To optimise efficiency, SISA combines the surfaces of the IFU with those of the spectrograph using only three surfaces in total, one for the telescope and two for the instrument. SISA design is based on an idea proposed in 2018 by A. Calcines[13] et al. for ultra-compact integral field spectrographs for space applications. The conceptual optical design for SISA, showing only ten configurations is shown in **Figure 3**.

The telescope is composed of only one off-axis parabolic mirror with 200mm diameter and an effective focal length of 3 metres, providing an F/15 beam. The aperture was selected to optimise throughput with respect to other EUV instruments. The effective focal length was chosen after a trade-off study considering a spatial resolution of 1” and the minimum curved slicer mirror width that is currently feasible (15 microns). At the telescope focus an array of 100 curved slicers of 15 microns width by 3.64mm length will divide the field generating a pupil per slice. At the pupil positions the gratings will be located. Two alternatives are currently being studied: the use of a curved grating per slice, where each one will produce the spectrum associated to a slice of the field or the use of two larger curved gratings. The number of gratings will be defined after the optimisation of the optical design based on the optical quality. The curved gratings disperse the light producing the spectral decomposition of the beam into its constituent wavelengths and focus the beams on the detector combining the functionalities of the grating and the camera in a standard spectrograph. The use of individual gratings provides flexibility in the geometrical distribution of the spectra on the detector or detectors since each grating will have a different orientation (tilt angle around the X-axis and tilt angle around the Y-axis). At the moment, two detectors of 10 microns square pixel size are considered. A multi-layer coating optimised for the two considered spectral windows will be used for all optical surfaces.

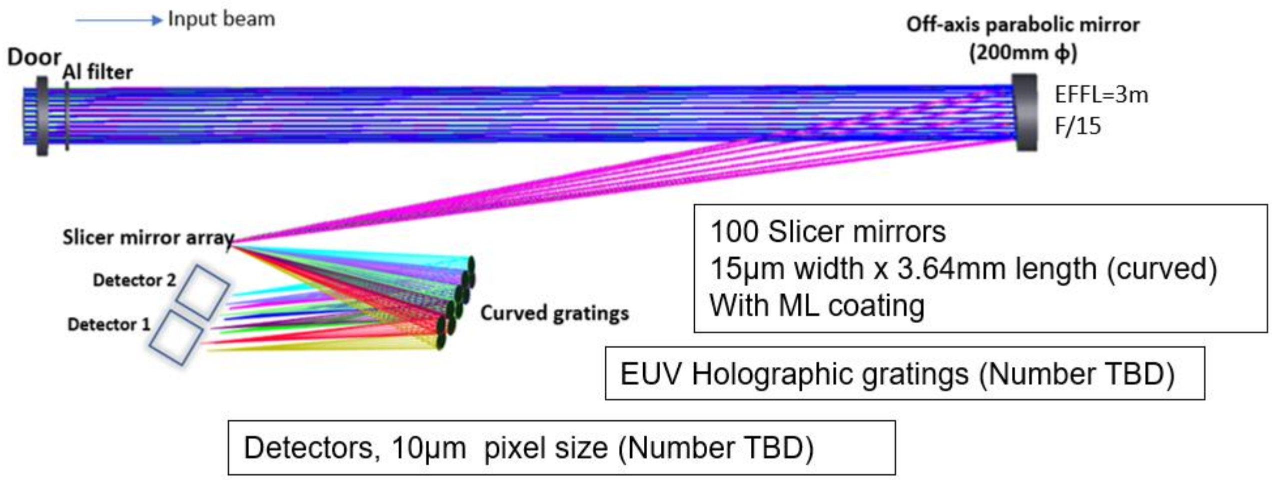

Figure 3. SISA conceptual optical design showing only ten configurations out of 100.

The main characteristics of SISA are:

- It will provide the spectra of all points of a 2-D field of view simultaneously within one exposure using the image slicer technology.
- It does not require any scanning mechanisms.
- The gratings are fixed.
- It does not have an entrance slit.
- It is highly efficient. It uses the minimum number of optical surfaces: two for the instrument and one for the spectrograph.

3.3 Critical points

Since image slicers have not yet been developed for the EUV, a plan to elevate the TRL up to TRL 6 within two years has been defined, which is shown in **Table 2**. Those tasks marked with an asterisk have already started. The preliminary design and the trade-off studies developed to evaluate the achievement of the specifications identified all critical points, which will be studied during the design phase. Both slicer options: glass slicers and metallic slicers, are being studied in parallel to evaluate performance and manufacturing capabilities for the EUV. For the glass slicer alternative, we are working with Bertin Winlight, world leaders of manufacturing of glass slicers. The manufacturer considered for the metallic solution is CANON, who has experience manufacturing image slicers for solar space projects in the UV and FUV. A multi-layer coating for the two spectral windows is being designed. A prototype will be manufactured with the design coating, and it will be tested in the relevant environment to demonstrate the feasibility of the proposed technology.

Table 2. Main tasks defined to elevate the TRL of the image slicers for the EUV up to TRL 6 within two years. The tasks marked with an asterisk have already started.

Tasks to increase slicers TRL	
Preliminary optical design	*
Trade-off studies to identify critical parameters	*
Manufacturing tests on glass slicer mirrors	*
Manufacturing tests on metallic slicer mirrors	*
Design of multi-layer coatings	*
Manufacturing of an image slicer demonstrator	
Deposition of designed coatings on slicer prototype	
SISA prototype	
Testing of prototype in relevant environment	

4. CONCLUSIONS

The main conclusions obtained from this study are listed below:

- Integral Field Spectroscopy is a key technique for the study of 2-D structures and the properties of the magnetic field.
- This technique has not been used for the Extreme Ultra-Violet yet.
- SISA is the first proposed integral field spectrograph using image slicers in the EUV.
- 2D spectral images will be created in seconds (over two orders of magnitude faster than the status quo), with enough spectral resolution to measure the properties of the plasma environment.
- For the manufacturing of glass slicers the considered manufacturer is Bertin Winlight, world leaders of glass slicers manufacturing.
- For the manufacturing of metallic slicers the considered manufacturer is CANON, with previous experience in the UV and FUV for solar space applications.
- We expect that the developments for SISA also benefit the community for other future integral field spectrographs using the image slicer technology in the EUV.

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