The State-of-the-Art of Image Slicers: Best Performance and Characteristics Obtained in Glass and Metal

Ariadna Calcines*[a], Sarah Matthews[b], Hamish Reid[b], Paul White[a]
[a]Centre for Advanced Instrumentation, Department of Physics, Durham University, UK; [b]University College London, Mullard Space Science Laboratory, UK.

ABSTRACT

Image slicer technology has undergone great developments in the last decades. Innovative solutions are proposed for the largest night-time and solar telescopes, as well as for space applications. The science cases for the next generation of instruments require pushing image slicer technology beyond its current limits. Future developments are focused mainly in two key parameters: the reduction of the slicer mirror width and the improvement of the surface roughness.

The need for narrower slicer mirrors to achieve higher resolution, better surface roughness to reduce stray light, and innovative ideas for highly efficient Integral Field Spectrographs are investigated in two projects: MINOS and LUCES developed in the UK by a consortium between Durham University and University College London. The main results are presented in this manuscript.

Keywords: image slicers, IFU, IFS, EUV Spectroscopy, UV, EUV.

1. INTRODUCTION TO IMAGE SLICERS

Due to the ability of Integral Field Spectrographs (IFS) to provide the spectra of a 2-D field of view simultaneously, these can be found in all ground-based telescopes, both for night-time observations and for solar physics.

The combination of an Integral Field Unit (IFU), to decompose and reorganise the field into the spectrograph entrance slit, with the spectrograph components, allows us to obtain the spectra within the same atmospheric conditions, without moving mechanisms such as field of view scanning systems, significantly reducing image cadence. There are different alternatives of Integral Field Unit: microlenses, optical fibres and image slicers (Figure 1).

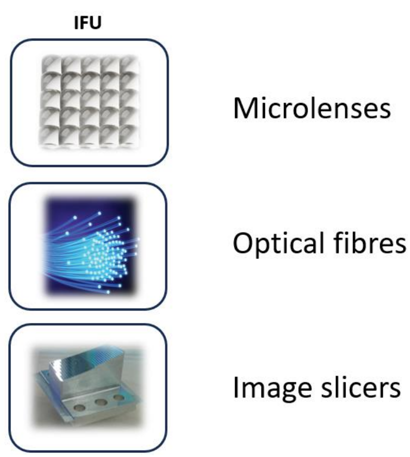


Figure 1. Alternatives of Integral Field Unit (IFU): microlenses, optical fibres and mage slicers. [Image credits: Microlenses from NALUX; fibres from tutorialspoint and slicer mirror array from Durham University.]

*ariadna.calcines@durham.ac.uk; phone +44 1913344814/43908;

Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation VI,
edited by Ramón Navarro, Ralf Jedamzik, Proc. of SPIE Vol. 13100, 131001P

Microlenses are a good solution for compact IFS observing in a narrow spectral range. For a wider range of wavelengths, microlenses present chromatism. Although this option presents the advantage of working in transmission, its application leads to spectra overlapping. This can be solved when combining microlenses and optical fibres. This option is optimum for large fields of view (FOV) and for Multi-Object Spectroscopy (MOS). However, optical fibres present low transmission in some spectral ranges; they suffer from focal-ratio degradation; they are depolarisers, which is very important for Solar Physics where often polarimeters are combined with spectrographs to perform Integral Field Spectro-Polarimetry, and they are sensitive to in-flight effects, which is a limiting factor for space applications.

Image slicers solve the problems presented by the other IFU alternatives. They are highly efficient, coupling the telescope to the instrument minimizing light losses; they are very compact and lightweight; they do not present focal-ratio degradation and they can be designed to offer a magnification if required; they define the spectrograph entrance slit dimensions, thus defining the sampling, related to spatial resolution and contributing to the spectral resolving power; they control the position of the exit pupil, which is important for telecentric systems and they do not have polarisation effects. A comparison of these three alternatives is presented in Figure 2.

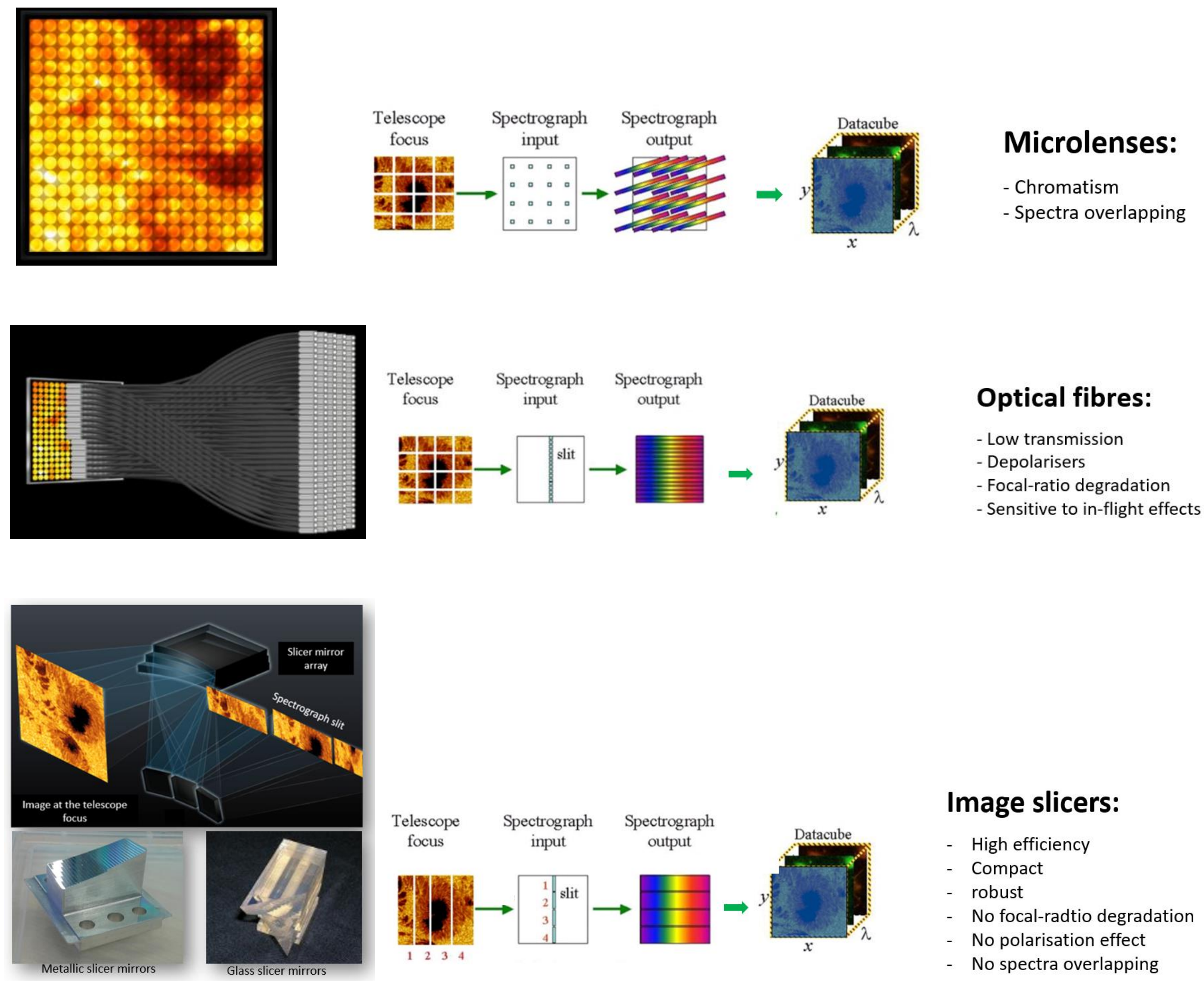


Figure 2. IFU alternatives and comparison of characteristics. Image credits for the slicer arrays: metallic slicers from Durham University (CfAI) and glass slicers from Bertin Technologies.

2. APPLICATIONS AND CHALLENGES

With all the advantages mentioned in Section 1, image slicers can be found in IFS operating at different wavelengths and for different science cases. Some examples of instruments using image slicers and their spectral ranges are presented in Figure 3. For ground-based telescopes, image slicers are operating in the visible and infrared spectral ranges, for night-time observations, like: VLT [1], Gemini North [2], GTC [3], also proposed for ELT [4], and for solar telescopes like: GREGOR [5] and EST [6]. There are also image slicers in space, in the infrared spectral range on-board the James Webb Space Telescope [7,8]. In the last years the developments in this technology extended to applications at shorter wavelengths, for CUBES [9] (300-400nm), INFUSE [10] in the FUV (100-200nm) and currently being proposed for Integral Field Spectroscopy in the Extreme Ultra-Violet for the instrument SISA [11] (18-25nm).

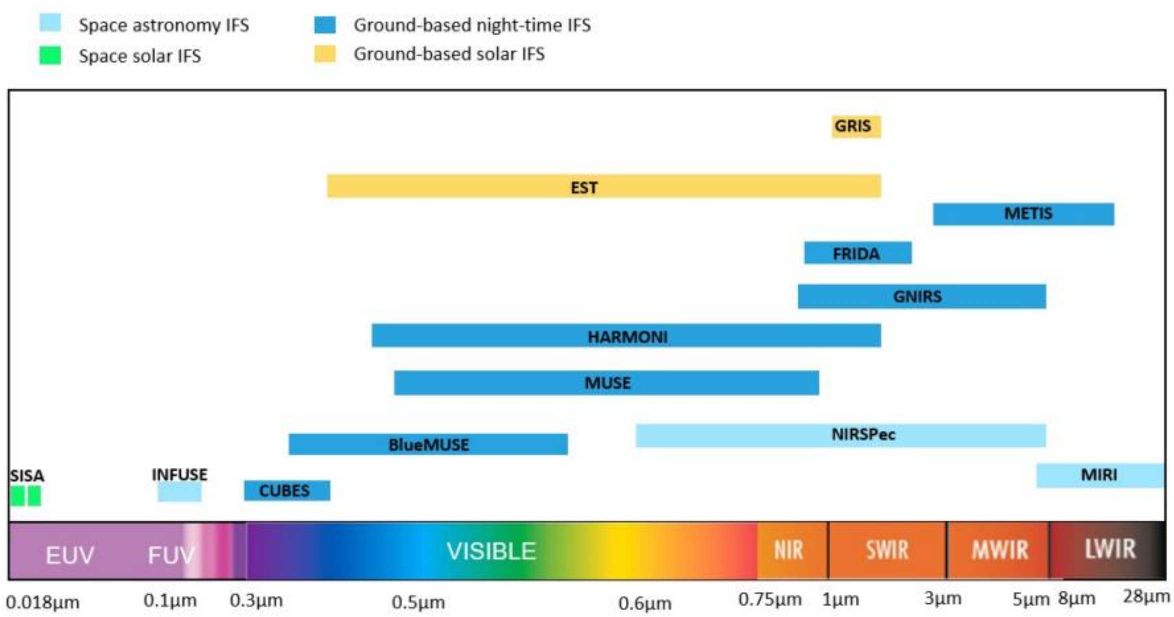


Figure 3. Some examples of instruments using image slicers and their spectral ranges.

Table 1. Examples of width and curvature of slicer mirrors required for IFS for different science cases.

Instrument	Telescope	Application	Width of slicer mirrors	Slicer curvature
CUBES – low resolution mode	VLT	Night-time ground-based	2mm	Spherical
MUSE	VLT	Night-time ground-based	0.9mm	Spherical
CUBES – high resolution mode	VLT	Night-time ground-based	0.5mm	Spherical
GNIRS-HR mode	Gemini North	Night-time ground-based	410 µm	Spherical
GRIS	GREGOR	Solar ground-based	100 µm	Flat
IFS for EST	EST	Solar ground-based	50 µm	Flat
SISA	SPARK (proposal)	Solar space	15 µm	Spherical

From the three mentioned IFU alternatives, image slicers are the most contemporaneous. Although a more recent technology than microlenses or optical fibres their advantages have led to a rapid development of creative solutions whose specifications challenge the current limits of technology. Their application extends to: ground-based night time and solar observations and space.

At shorter wavelengths surface roughness is a very important factor, requiring the achievement of lower values to minimise stray light. The width of the slicer mirror depends on the science cases and the required resolution. Table 1 shows some examples for different applications. Solar Physics requires higher resolution (spatial and spectral), which implies thinner slicer mirrors. The thinnest slicer mirrors ever proposed are those for SISA [11], with a width of 15µm. This instrument is still at proposal level.

1.1 Night-time

For ground-based night-time IFS, there are image slicers applied to a wide range of wavelengths from the infrared, for example in the instrument GNIRS [2] for the Gemini North Telescope to the UV/Visible, for VLT CUBES [9]. The shorter the wavelength the more challenging is the development of the image slicer, especially in terms of surface roughness, directly related to stray light. For UV applications where the photons flux is low, the design is limited to the minimum number of optical components to maximise throughput; and to the lowest surface roughness to minimise stray light, which demands the application of glass slicers, which can be polished obtaining better results. The substrates considered for this spectral range are either Fused Silica or Zerodur. Fused Silica is recommended for a better match with the coefficient of thermal expansion (CTE) of Invar, which is often used for mechanical parts. A typical value for the surface roughness achievable in glass is 1nm RMS.

1.2 Solar

Solar spectrographs achieve very high resolution, both spatial and spectral. For a given field of view, the higher the resolution, the narrower the slicer mirrors need to be. This is a great challenge, with more difficulty to be achieved in powered slicers than in flat, and more difficult in glass than in metal. Table 1 shows some examples of slicer mirrors widths for different IFS. Comparing these values, the width required for the high resolution integral field spectrograph of the European Solar Telescope (EST) [12] is one order of magnitude narrower than the value for the high resolution mode of VLT CUBES [13].

1.3 Space

There are image slicers in space too, operating in the infrared on-board the James Webb Space Telescope in NIRSpec [8] and MIRI [7]. These image slicers were manufactured in metal.

The next generation of solar space missions [14] requires Integral Field Spectroscopy at shorter wavelengths with high: spatial, spectral and temporal resolutions. The most challenging specifications to date for the width of slicer mirrors has been proposed for SISA (Spectral Imaging of the Solar Atmosphere) [15], the first integral field spectrograph using image slicers in the Extreme Ultra-Violet regime. SISA requires the observation in two spectral windows simultaneously centred at 18nm and 25nm, with a spectral resolution of 0.05Å FWHM, a spectral resolving power, R of 3650-5160, depending on the wavelength; covering a field of view of 100arcsec x 250arcsec; a spatial resolution of 1arscec in two pixels resolution element and a temporal resolution of 1second for high signal and 10seconds for low signal.

This instrument presents all kind of challenges:

- It is the first time that Integral Field Spectroscopy (IFS) is proposed for the EUV.
- SISA requires a width of the slicer mirrors of 15µm, the thinnest ever proposed, never achieved before.

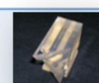
- Since the image slicer technology has not been applied in the EUV before, its Technology Readiness Level (TRL) is still low to be considered for space missions and requires development.
- Powered slicer mirrors are needed for this proposal to combine the functionalities of the IFU and spectrograph minimising the number of optical components to optimise efficiency. In glass, it is more difficult to manufacture thinner slicer mirrors on curved substrates. In this case, the curvature of the slicer mirrors and the specification for the width adds more complexity.
- Although thinner slicer mirrors are achieved in metal, the standard surface roughness values are not low enough for EUV applications. Two developments are possible: (1) the reduction of the surface roughness of metallic slicers or (2) the reduction of the width of glass slicer mirrors. Both studies have been developed within the projects LUCES and MINOS, respectively.

3. METALLIC VS GLASS

Image slicers can be manufactured in glass or metallic substrate with a coating on it selected to maximise the reflectivity at the spectral range of interest. Regardless of the substrate choice, image slicers are very compact and lightweight. Each substrate presents some advantages, and the ideal choice depends on the application.

Since glass slicers can be polished, these present the best surface roughness, minimising stray light and offering very low coefficient of thermal expansion (CTE). Metallic slicers have a higher CTE, however, in this case, the whole instrument can be made of the same material for a uniform response to thermal changes. Both solutions are robust, specially the metallic one, which is manufactured as a monolithic piece, while glass slicers are manufactured individually and assembled afterwards. Flat and spherical slicer mirrors are currently possible in both materials. Metallic slicers offer more flexibility to manufacture more complex curvatures, such as aspheres or freeform and it is possible to achieve narrower widths for the slicer mirrors, which is important to achieve high resolution. A comparison of their characteristics is presented in Table 2. The asterisks represent the slicer alternative that presents the best results for the parameter evaluated in the first column on the left.

Table 2. Comparison of characteristics of glass and metallic slicers. The asterisks represent the slicer alternative that presents the best results for the parameter evaluated in the first column on the left.

	Glass slicers 	**Metallic slicers** 
Surface roughness	*	
Low CTE	*	
Robust	*	**
Thinner slicer width		*
Complex curvature on slicers		*
High efficiency	*	*
Compact	*	*

Based on the advantages of each slicer alternative, both solutions have been studied in parallel, the developments of glass slicers within the project MINOS and the improvements on metallic slicers within LUCES.

4. MINOS

MINOS (**M**anufacturing of **I**mage Slicer **No**vel technology for **S**pace) is a project funded by Durham University in which a glass slicer prototype was manufactured by Bertin Technologies (former Winlight Optics) with the goal of researching the minimum width and minimum surface roughness achievable on spherical slicer mirrors. The slicer prototype is shown in Figure 4, where the slicer mirrors can be found within the wider blocks of Fused Silica.

The results of MINOS constitute the state of the art of glass slicers. The best results obtained in glass before this project included a width of 100μm for flat slicer mirrors with a typical surface roughness of 1nm RMS. MINOS has achieved 0.2 nm RMS on spherical slicer mirrors of 70μm width.

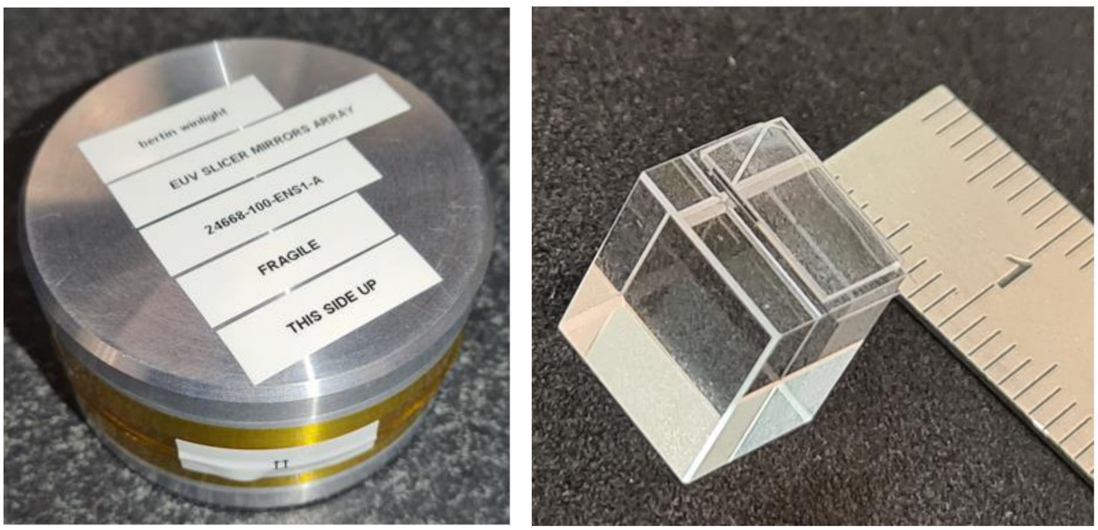


Figure 4. Glass slicer prototype produced by Bertin Technologies for the project MINOS with spherical slicer mirrors of 70μm width and 0.2nm RMS surface roughness.

5. LUCES

LUCES (**L**ooking **U**p image slicers optimum **C**apabilities in the **E**UV for **S**pace) is funded by the UK Space Agency and will produce nine slicer demonstrators (Table 3) focused on two studies:

(1) <u>Evaluation of the minimum slicer mirror width achievable in metal:</u>

Five demonstrators with six slicer mirrors each will be produced with slicer mirrors widths of: 350 μm, 70 μm, 50 μm and 15 μm considering spherical slicer mirrors. For 70 μm, two demonstrators will be manufactured, one using spherical slicer mirrors and another with flat slicers to compare these results with the ones obtained in MINOS.

The widths of the slicers have been defined based on the following: a width slightly thinner than the thinnest slicers we have produced at Durham University (410μm for the high resolution mode of GNIRS/Gemini North [2]); the same width used for MINOS, 70 μm, to compare results in metal and glass; 50 μm as required for the Integral Field Spectrograph of the European Solar Telescope and 15 μm based on the specifications for SISA.

(2) Reduction of the surface roughness for metallic slicers:

The 70 µm spherical slicer mirrors demonstrator was manufactured in five metallic materials to determine which one offered the best surface roughness results: Aluminium RSA, NiP, Brass, Nickel Silver and Copper.

The main characteristics of the nine slicer demonstrators for LUCES are presented in table 3. The spherical slicer mirrors have a radius of curvature of 200mm. The length of the slicer mirrors is 5mm. Figure 5 shows the Al RSA demonstrator with six spherical mirrors of 70 µm width.

Table 3. Nine slicer demonstrators produced for LUCES.

Demonstrator #	Slicer width	Curvature	Material
1	350 µm	spherical	Al RSA 6061
2	70 µm	spherical	Al RSA 6061
3	50 µm	spherical	Al RSA 6061
4	15 µm	spherical	Al RSA 6061
5	70 µm	flat	Al RSA 6061
6	70 µm	spherical	Al RSA 443+ NiP
7	70 µm	spherical	Brass
8	70 µm	spherical	Nickel Silver
9	70 µm	spherical	Copper

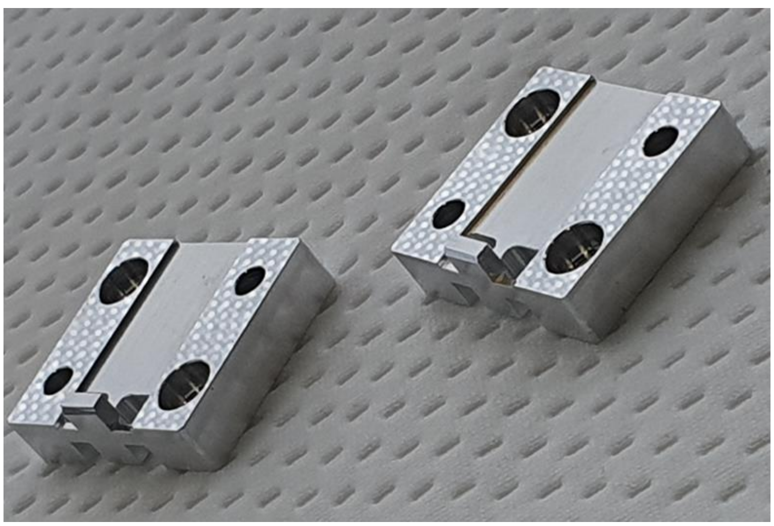
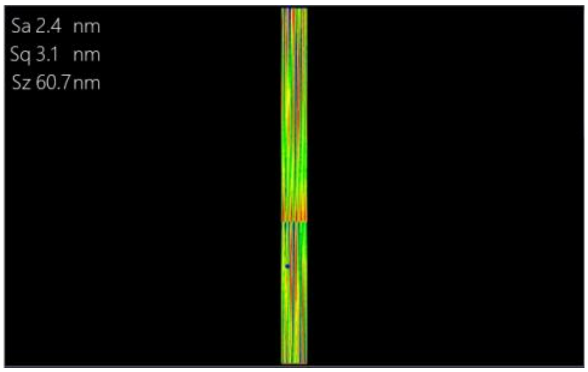


Figure 5. Two Al RSA 6061 slicer demonstrators with six spherical slicer mirrors of 70 µm width.

The results obtained for the surface roughness for the five considered materials are presented in Table 4. The best results were obtained for NiP, followed by Al RSA 6061. The rest of materials were considered for research purpose, but they are not common materials used for the metallic slicers that we produce in Durham. The results of the roughness measurements (parameter Sq) for NiP and Al RSA 6061 on 70µm spherical slicer mirrors are presented in Figure 6.

Table 4. Surface roughness for different metallic substrates.

Material	Surface Roughness [nm RMS]
NiP	3.1
Al RSA 6061	3.8
Brass	4.4
Copper	5.0
Nickel Silver	5.2



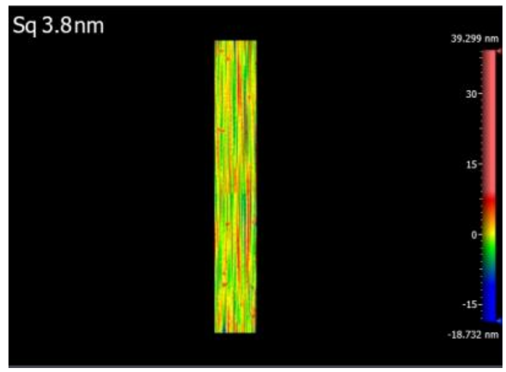


Figure 6. Left: Best surface roughness obtained for the NiP slicer demonstrator, 3.1nm RMS. Right: Measurement of the surface roughness of slice# 3 of the LUCES demonstrator #2, with a 70µm width, 5mm length, spherical shape (radius of curvature of 200mm) made on Al RSA 6061, 3.8nm RMS.

6. IMPROVEMENTS IN IMAGE SLICERS

MINOS and LUCES have led to improvements in the results that can be achieved in glass and metallic slicer mirrors. A comparison between the previous best results and what is currently possible is presented in Table 5.

For glass slicer, an improvement in surface roughness from a typical value of 1nm RMS to 0.2nm RMS. More complex slicer mirrors are now possible too, from a minimum 100 µm width achievable in flat substrates to a reduction of the width achieving 70µm width for spherical slicers.

For metal, the typical surface roughness of 4 nm RMS has been improved achieving 3.1nm RMS. The major development in metal is the reduction of the slicer width, from a previous minimum width of 410µm to the production of slicers with a width of: 350µm, 70µm, 50µm and 15µm.

Table 5. Comparison between the best results obtained previously and the improvements achieved.

	Glass slicers		Metallic slicers	
	Previous results	**Achieved**	**Previous results**	**Achieved**
Surface roughness	1 nm RMS	0.2 nm RMS	4 nm RMS	3.1 nm RMS
Minimum width	100µm (flat)	70µm (spherical)	410µm (spherical)	15µm (spherical)

ACKNOWLEDGEMENTS

ACR acknowledges Durham University Seedcorn Funding for MINOS and the UK Space Agency, which funded LUCES within the ETP programme. ACR also would like to acknowledge the Centre for Advanced Instrumentation of Durham Univertsity for the developments in metallic slicers and Bertin Technologies for the developments in glass slicers. Special thanks to Yves Salaun, whose dedication to the development of image slicers made possible all the current achievements for the astronomical community. SAM and HASR acknowledge funding from the STFC Consolidated Grant ST/W001004/1.

REFERENCES

[1] Florence Laurent, Louisa Adjali, James Arns, Roland Bacon, Didier Boudon, Patrick Caillier, Eric Daquisé, Bernard Delabre, Jean-Pierre Dubois, Philippe Godefroy, Aurélien Jarno, Paul Jorden, Johan Kosmalski, Vincent Lapère, Jean-Louis Lizon, Magali Loupias, Arlette Pecontal, Roland Reiss, Alban REMILLIEUX, Edgar Renault, Gero Rupprecht, Yves Salaun, "MUSE integral field unit: test results on the first out of 24", Proc. SPIE 7739, 77394m (2010).

[2] Ariadna Calcines Rosario, Cornelis M. Dubbeldam, Ray Sharples, Cyril Bourgenot, Ruben Diaz, Andrew W. Stephens, "The HR image slicer for GNIRS at Gemini North: optical design and performance", Proc. SPIE 12184, 121840L (2022).

[3] Salvador Cuevas, Stephen Eikenberry, Beatriz Sánchez, "FRIDA integral field unit manufacturing", Proc. SPIE 9151, 91514N (2014).

[4] J. Kosmalski, M. Tecza, I. Bryson, F. Clarke, D. Freeman, M. Loupias, J.E. Migniau, A. Remillieux, N.A. Thatte, "Preliminary design study of the integral field unit for the E-ELT Harmoni instrument", Proc. SPIE 9908, 99089T (2016).

[5] A. Calcines, R. L. López, M. Collados, N. Vega Reyes, "Música image slicer prototype at 1.5-m GREGOR solar telescope", Proc. SPIE 9147, 914731 (2014).

[6] A. Calcines, R. L. López, M. Collados, "Música: THE MULTI-SLIT IMAGE SLICER FOR THE EST SPECTROGRAPH", Journal of Astronomical Instrumentation, Vol. 02, No. 01 (2013).

[7] M. Wells, D. Lee, A. Oudenhuysen, P. Hastings, J.W. Pel, A. Glasse, "The MIRI medium resolution spectrometer for the James Webb Space Telescope", Proc. SPIE 6265, 626514 (2006).

[8] Florence Laurent, Christophe Bonneville, Pierre Ferruit, Francois Henault, Jean-Pierre Lemonnier, Gabriel Moreaux, Eric Prieto, Daniel Robert, "Optical design, fabrication, and testing a prototype of the NIRSPec IFU", Proc. SPIE 5252 (2004).

[9] A. Calcines, M. Wells, K. O´Brien et al., "Design of the VLT-CUBES image slicers: field re-formatters to provide two spectral resolutions", Experimental Astronomy55, 267-280 (2023).

[10] Emily M. Witt, Brian T. Fleming, James C. Green, Kevin France, Jack Williams, Takashi Sukegawa, Oswald Siegmund, Dana Chafetz, "INFUSE: a rocket-borne FUV integral field spectrograph", Proc. SPIE 11444 (2020).

[11] Calcines Rosario, A.; Auchère, F.; Corso, A.J.; Del Zanna, G.; Dudík, J.; Gissot, S.; Hayes, L.A.; Kerr, G.S.; Kintziger, C.; Matthews, S.A.; et al. "Spectral Imager of the Solar Atmosphere: The First Extreme-Ultraviolet Solar Integral Field Spectrograph Using Slicers". MDPI Aerospace , *11*, 208. (2024).

[12] A. Calcines, R. L. López, M. Collados, "A HIGH RESOLUTION INTEGRAL FIELD SPECTROGRAPH FOR THE EUROPEAN SOLAR TELESCOPE", Journal of Astronomical Instrumentation, Vol. 02, No. 01 (2013).

[13] Ariadna Calcines, Martyn Wells, Kieran O´Brien, Simon Morris, Walter Seifert, Alessio Zanutta, Chris Evans, Paolo Di Marcantonio, "CUBES: application of image slicers to reformat the field for two spectral resolving powers", Proc. SPIE 12188, 1218827 (2022).

[14] Reid, H.A.S.; Musset, S.; Ryan, D.F.; Andretta, V.; Auchère, F.; Baker, D.; Benvenuto, F.; Browning, P.; Buchlin, É.; Calcines Rosario, A.; et al., "The Solar Particle Acceleration Radiation and Kinetics (SPARK) Mission Concept". MDPI Aerospace, 10, 1034. (2023).

[15] Ariadna Calcines Rosario, Sarah Matthews, Hamish Reid, "Exploring the application of image slicers for the EUV for the next generation of solar space missions", Proc. SPIE 12181, 121810K (2022).