High efficient inexpensive 2-slices image slicers

Gerardo Avila*[a], Carlos Guirao[a], Thomas Baader[b]
[a]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Muenchen, Germany
[b]Baader Planetarium, Zur Sternwarte, 82291 Mammendorf, Germany

ABSTRACT

Image slicers are widely used in astronomical instrumentation to increase the resolving power of spectrographs with the maximum throughput. However, the manufacturing costs are usually significant. This paper describes new image slicer simple designs. They provide only two slices but with high throughput and low cost manufacture process. Two prototypes have been evaluated and their performances are reported.

Keywords: Image slicers, spectrographs, high spectral resolution

1. INTRODUCTION

A number of image slicers have been installed in instruments like CES[1], FEROS[2], 3D[3], MUSE[4]. They basically use Bowen-Walraven prisms (CES, FEROS) or stack of slabs (3D, MUSE).

Bowen-Walraven image slicers use a thin glass plate where the light is transmitted along by total internal reflection (Figure 1). A base prism with a sharp edge is glued to the plate by molecular contact to “cut” the internal reflection of the transmitted beam. By choosing an appropriate configuration, the slices are arranged on a line simulating the slit of the spectrograph.

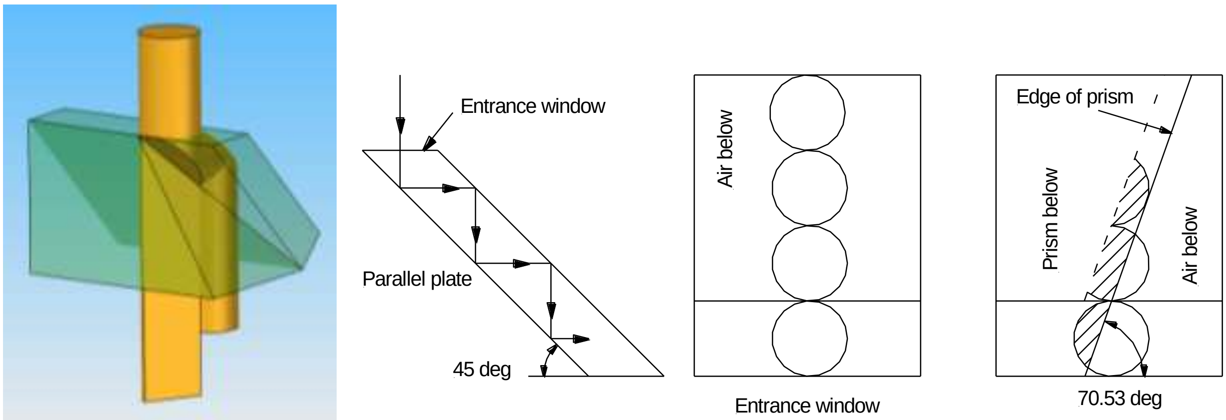

Figure. 1.The typical Bowen-Walraven image slicer. From left: 3D view showing the plate, base prism and incoming beam, Parallel plate showing the total internal transmission. Top view: footprint of the incoming beam and its successive internal reflections along the plate. Plate and prism showing the slices. This configuration is made for 3 slices.

The optical efficiency of the slicer is limited by the internal absorption of the glass, the Fresnel reflection losses at the input and output surfaces and mostly by the quality of the sharp edge of the base prism. The plate and prism are usually made in silica, so the absorption is almost zero. Therefore the throughput depends on the sharpness of the prism edge and the anti-reflection coating on the surfaces.

The Bowen Walraven image slicer shows two important advantages:

* gavila@eso.org, tel + 49 89 32006394, fax + 49 89 3202362, www.eso.org

1. High efficiency. Throughputs more than 90% have been reported[1].
2. A big light spot may be sliced several times. Therefore the resolving power of a spectrograph may be substantially increased with a high throughput. As an example, in the fibre link between the 3.6 m telescope in La Silla and the CES spectrograph, the image slicer No, 3 slices 10 times the image of the fibre.

Unfortunately there are a number of disadvantages limiting its scope of applicability:

1. The equivalent slit is inclined along the optical axis (out coming beam) of the spectrograph collimator (Figure 1, left picture). The image of the slit projected on the detector has therefore a ‘corset’ shape: it is sharp at the middle of the slit and progressively defocused towards the edges. This problem reduces slightly the resolving power of the spectrograph. This tilt may be reduced by re-shaping the exit face of the base prism, but this increases the complexity of the device making the manufacturing process more expensive.
2. The glasses usually are silica to ensure high throughput. However the refraction index of the silica is relatively low and therefore the critical internal reflection angle limits the aperture beam to around F/11 or slower.
3. The cost of the entire device is usually very high. The plate must be very thin, especially for small spots to be sliced (< 1 mm) and the base prism carefully cut and polished. The edge of the slicing face must be very sharp to ensure a good quality of the edges of the slit. In addition, the pieces must be glued by molecular contact, which is not a standard technique for all optical manufacturers.

We propose an image slice based on the same principle but using mirrors instead of a glass plate working by total internal reflection. This new design can be manufactured with two simple mirrors reducing considerably the manufacturing costs,

2. MIRRORS IMAGE SLICER

With the same principle, the silica plate in the traditional Bowen-Walraven image slicer could be replaced by two parallel mirrors in order to generate the successive reflections. The edges of the mirrors are placed in such a way that a portion of the beam is not anymore reflected but leaving the arrangement towards the spectrograph. Figure 2 shows the optical layout.

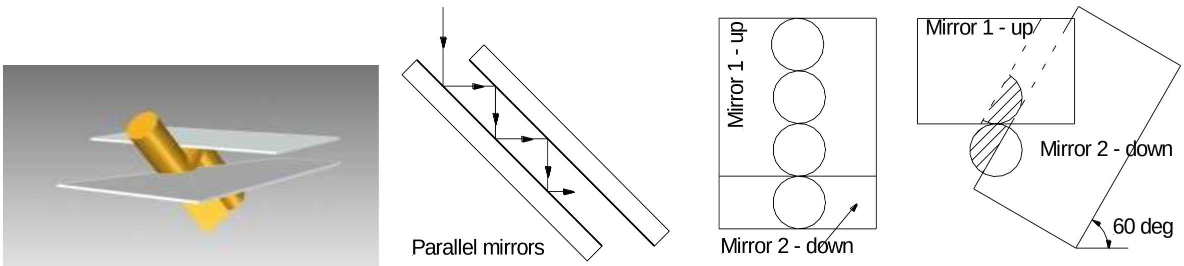

Figure 2. Concept of the image slicer with mirrors. From left: 3D view. Parallel mirrors showing the reflection of the input beam. Top view showing the entrance slit and blue print of the successive reflections of the incoming beam. The lower mirror is turned to allow half of the beam leaving the device and the second half to be reflected by the lower mirror. The angle between the mirrors provides just two slices

The light spot is placed in the corner between the two mirrors. It touches the edge of mirror-1 in such a way that the half the spot surface is cut by mirror-2. Under this condition, half of the beam is transmitted directly to the spectrograph and the other half is reflected two times by both, mirror-2 and mirror 1. Since the edge of this mirror is inclined with respect to the direction of the successive footprints of the input beam, the second half of the beam will leave without anymore reflections.

The mirror-2 which is below mirror-1 is twisted by an appropriate angle (60° from the top view, 67.8° on the plane of the mirrors) to get two slices. For three slices, the projected angle between the mirrors (edges) has to be 70.53°. The equation 1 provides the angle between the mirrors (φ) as seen from the top (incoming beam) as a function of the number of slices n. Equation 2 gives the angle θ between the mirrors but on their surfaces plane.

$$\varphi = \cos^{-1}(1/n) \qquad (1)$$

$$\theta = \tan^{-1}(\sqrt{2} \cdot \tan\varphi) \quad (2)$$

If the mirrors are placed at 45°, the required separation *d* between them is

$$d = \phi / \sqrt{2} \quad (3)$$

where *phi* is the diameter of the spot at the entrance of the image slicer.

About the efficiency of the mirror array, the first slice goes through without looses. The second slice suffers two reflections. If *R* is the reflectivity of the mirrors, the second slice will have an efficiency of R^2 and therefore the total efficiency *T* will be

$$T = 50 \cdot (1 + R^2) \quad (4)$$

$T \approx R$, when $R \approx 1$

A good aluminum coating will have a reflectivity in the visible range of around 92% (R=0.92), therefore the throughput for a 2 slices device will be close to 92%. For a silver coating the efficiency of the image slicer would reach 95%!

In a general case, when *n* is the number of slices, the throughput (*T* in %) of this image slicer will be:

$$T = \frac{100}{n} \cdot \sum_{i=1}^{n} R^{2(i-1)} \quad (5)$$

where 0< R < 1

If an image slicer is configured to have 3 slices, its efficiency will be 85.4% for aluminum coating. As the total efficiency decreases rapidly with the number of slices, our proposed model would be optimal for a two slices configuration. The traditional Bowen-Walraven has a better efficiency because the losses along the glass plate are almost 0%. Theoretically it is limited only by the reflection losses at the input and output surfaces of the plate and base prism respectively.

The tilt of the slit plane with respect to the optical axis is similar to the one produced by the prisms image slicer. In our case the mirrors are placed at 45° and therefore the slit tilt with respect to the out coming beam will be also 45°.

IF only 2 slices are produced, this tilt generates a negligible defocusing effect of the slit on the detector.

Image slicers can be installed directly at the focal plane of the telescope, i.e. when the spectrograph is mounted to the telescope. However, in practical cases, the spectrograph is linked to the telescope through an optical fibre and therefore the fibre output end is imaged on the entrance of the image slicer.

Figure 3 shows a prototype for 2 slices. We used a 50 µm core diameter fibre working at F/5 and a small doublet to project the fibre output end on the image slicer with a spot of 200 µm (F/20 output beam).

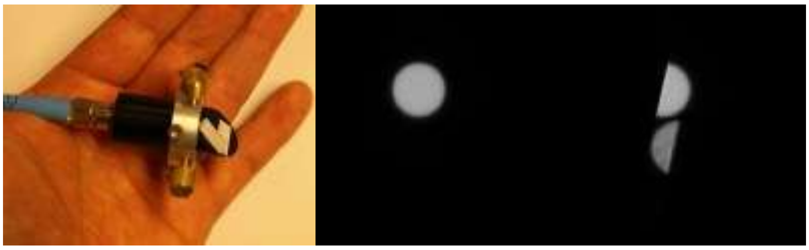

Figure 3. A two mirrors image slicer prototype

We made the mirrors with aluminized microscope cover glass. The edges are intrinsically well defined and they do not need to be re-sharpened. The separation between the mirrors was achieved by gluing a third cover glass in between. Usually the thickness of these plates range between 140 and 160 µm. So very close to the required thickness (141.4 µm).

After assembling, the resulting slit width was 103 µm. The roughness of the slit edges were estimated to less than 5 µm peak to valley. From Figure 3 we clearly see the intensity difference between the transmitted and reflected slices due to the low reflectivity of the applied aluminum coating. The measured total efficiency of the prototype was only 85%.

For any gap, we have foreseen mounting the upper mirror on a small plate where the separation between the mirrors can be adjusted freely (Fig. 4).

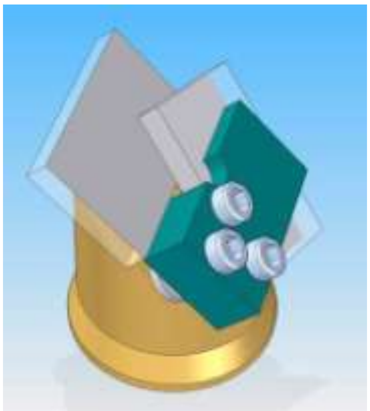

Figure 4. Proposed design for a general purpose image slicer with mirrors

3. GLASS SLABS IMAGE SLICER

A simple image slicer can be made with just two parallel plates tilted by a given angle one respect to the other. Figure 5 shows the concept.

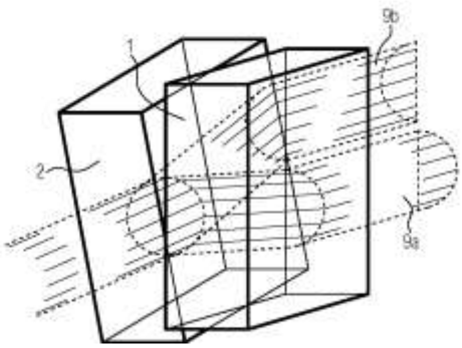

Figure 5. Image slicer made with two inclined parallel glass plates

The two glass slabs with parallel flat faces are in contact together. The contact surface of one of the slabs is aluminized. The slabs may be glued but the glue must have a refraction index lower than the glass in order to have total internal reflection. The slabs are placed each other with a small angle α between them.

A light spot is imaged just at the exit of the plates where their surfaces intersect. This intersection will act as the slit of the spectrograph. The light spot may be the image of a star provided by a telescope or any other light source to be analyzed by the spectrograph.

For simplicity, we have assumed an input parallel light beam. The spot is cut in two half-moons. The rays from one of them are refracted by the plate and leave parallel to the incoming beam but shifted by an amount depending on the surface angle, the optical path and refraction index of the plate. For small tilts of the plates, the shift s is given by

$$s \approx e \cdot a \cdot (1 - \frac{1}{n})$$

where e is the length of the individual plate, α the rotation angle of the plate and n the refraction index of the glass.

The other half-moon follows a similar shift after leaving the plate but in opposite direction. The contact surface between the plates has to be reflective in order to avoid contamination of rays between the two exit beams. One of the internal surfaces must be aluminized or the 2 plates can be assembled with glue having a refraction index lower than the glass in order to create total internal reflection. If the surfaces are just put in contact without strong pressure, the thin air film between the two plates is enough to produce total internal reflection.

Figure 6 shows the prototype (10x10x5 mm) and the aspect of the slices for a 100 µm spot diameter. The light beam was open at F/6.

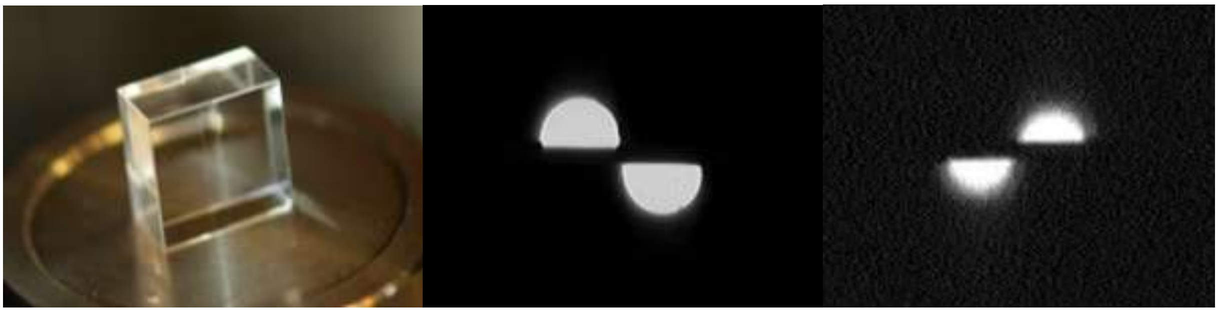

Figure 6.. Left: prototype of an image slicer made with two tilted plates. Middle: aspect of the slices for a 100 µm spot at F/6. Right: slices for a 50 µm spot also at F/6.

When feeding a spectrograph, the orientation of the 2 slices must be perpendicular to the dispersion. Each slice will generate its own spectrum. The spectra are shifted by the radius of the spot. The alignment and “binning” of the two spectra should be done by a proper data reduction.

As for the image slicer with mirrors, the optical efficiency is mainly driven by the quality of the sharpness of the two slabs. In a second order the transmission is given by the anti-reflection coating and the internal transmission of the glass. The later is negligible and the applied coating has reflection losses smaller than 1% in the 400 – 600 nm visible spectral range

The measured efficiency of the prototype was 92 % for the 100 µm spot at F/6 and 90% for an F/8 beam. Measurements for a 50µm spot are in process.

4. CONCLUSION

We presented in this article a prototype of a Bowen-Walraven Image Slicer made with mirrors. The advantages and drawbacks were analyzed. Best performances are achieved for an image slicer with only 2 slices. Our prototype provides a slit of 103 µm with a total efficiency of 85%.

We made a prototype of a slicer with two tilted glass plates. The resulting image quality is excellent for spots around 100 µm or bigger and acceptable for 50 µm spots. Its throughput was 90 % for a 100 µm spot generated by an F/8 beam.

These two concepts may be a good alternative to increase efficiently the resolving power of small spectrographs linked with optical fibres.

REFERENCES

[1] S. D’Odorico, G. Avila and P. Molaro. “More Light Through the Fibre: an Upgrading of the Link 3.6-m – CES”. The Messenger No. 58 ESO, Dec. 1989.

[2] A. Kaufer et al. “FEROS, the Fiber-fed Extended Range Optical Spectrograph for the ESO 1.52-m Telescope”. The messenger No. 89. Sep 1989.

[3] L. Weitzel et al. “3D: The new MPE near-infrared field imaging spectrometer”. Experimental Astronomy. Volume 3, Numbers 1-4 (1994)

[4] F. Laurent et al. “MUSE Image Slicer: Test results on largest slicer ever manufactured”. Proceedings of the SPIE, Volume 7018, pp. 70180J-70180J-12 (2008)

[5] G. Avila, Characterization of optical fibres for astronomical applications, 3 April 2009, http://spectroscopy.wordpress.com/2009/04/03/characterization-of-optical-fibres/