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An integral field spectrograph for the 4-m European Solar Telescope

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Abstract. This paper presents the proposal of a high resolution, integral field spectrograph that is currently being designed for the 4-meter aperture European Solar Telescope. This instrument is optimized for the study of the solar chromosphere and photosphere to allow the investigation of magnetic phenomena concentrated within these two layers. It will observe a bidimensional field of view of 80 arcsec^2 that is reorganized, using an integral field unit, into eight long slits of 200 arcsec length by 0.05 arcsec width. A new concept of image slicer has been specifically designed for this instrument. It is a telecentric system and, because of the symmetry of its layout, it presents several advantages, which are presented in this paper. The spectrograph will have capabilities to observe different layers of the Sun at the same time due to its multi-wavelength capability that allows the observation of 5 visible and 3 near-infrared wavelength intervals from 3900 to 23000 Å, with a spectral resolution of about 300,000. In addition, it is designed to offer two modes of operation: spectroscopic and spectro-polarimetric. The optical quality of the instrument is diffraction limited.

Key words. Astronomical instrumentation, methods and techniques – Instrumentation: spectrographs

1. Introduction

There are still a number of unknown issues about the Sun that require technologic step forwards. For this reason the European Solar Telescope project (EST) (Collados et al. 2010) is developed with the aim of designing and manufacturing a 4-m aperture solar telescope (Sánchez-Capuchino et al. 2010) and a broad variety of instruments that can operate simultaneously (Calcines et al. 2012a).

Spectroscopy is one of the most used techniques in solar physics to obtain information about the physical characteristics of the phenomena that take place in the solar atmosphere. Generally, it is combined with polarimetry to evaluate quantitatively the magnetic field vector in solar structures. These techniques are implemented in this instrument, which offers two different modes of operation: spectroscopic and spectro-polarimetric. The requirements for this spectrograph, as well as the proposed technical solution, are described in sections below.

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2. Requirements

The spectrograph (Calcines et al. 2011) is optimized for the observation of photospheric and chromospheric phenomena like: flux tubes, network elements, magnetic canopies, Hanle effect, flares or sunspots. The science programs (Calcines et al. 2010a) also include second priority programs for the observation of some planets, like Mercury, Venus or Jupiter.

The main requirements for the instrument are presented in Table 1. 4k × 4k detectors have been considered for the design of this instrument. The pixels sizes have been assumed within the standard interval, as 10 μm for visible wavelengths and 20 μm for the infrared ones.

The field of view (FoV) is cut in slices of 0.05 arcsec, what, for the F/50 telescope focal-ratio, implies a physical size of 50 μm.

In general for solar physics, and, especially for an instrument with the capabilities of this one, high spatial and spectral resolution are crucial. High spatial resolution is required to observe and study small structures. The science specifications for the spectrograph are a spatial resolution of 0.1 arcsec (2 pixels), what allows resolving structures about 140 km wide, and a spectral resolution of $R= \frac{\lambda}{\delta\lambda} \sim 300{,}000$.

The instrument covers a spectral range between 3900 and 23000 Å. Eight wavelengths (5 visible and 3 NIR) within this interval can be observed simultaneously, what allows the study of solar phenomena at different heights at the same time.

3. Instrument description

The proposed spectrograph (Calcines et al. 2010b) is a 1:1 F/40 system based on the Ebert-Fastie configuration, as a special case of the Czerny-Turner one, where collimator and camera mirrors are off-axis parabolic mirrors that belong to the same on-axis global parabola. It is preceded by a predisperser, with the same configuration, which acts as a prefilter. It uses a mask at its image focal plane to select the combination of wavelengths at the appropriate diffraction order. A mask per combination of wavelengths is needed.

It presents multi-slit capability for which eight entrance slits allow to increase the field of view observed in one exposure.

An integral field unit based on the image slicer concept decomposes a bidimensional 80 arcsec^2 field of view into eight slits of 200 arcsec length by 0.05 arcsec width. In addition, it transforms the telescope F/50 into the spectrograph F/40, for their perfect coupling.

With the application of integral field spectroscopy, the spectrum of all points of the 2-D field of view are obtained simultaneously and measured under the same atmospheric conditions. A larger field of view, up to 2 × 2 arcmin^2, is covered in sequential exposures using a bidimensional scanning system. Before the detectors, a reimaging system per wavelength is used to make a focal-ratio conversion from F/40 to F/10.3 for the visible wavelengths and F/20.6 for the infrared ones.

A detector per spectral range is required. Each detector is used for the observation of the spectra of the eight slits.

The optical design of the coupling between predisperser and spectrograph for the simultaneous observation of 2 wavelengths is shown in Fig. 2. The integral field unit (IFU) generates the eight entrance slits for the predisperser. At the predisperser image focal plane a mask selects the combination of wavelengths to be observed with the spectrograph. At the spectrograph image focal plane, the spectra corresponding to the eight entrance slits are formed in each wavelength interval (centered around λ_1 and λ_2 in the example).

The spectrograph offers 2 modes of operation: spectroscopic and spectro-polarimetric. For the spectroscopic one, an entrance field of view of 80 arcsec^2 is reorganized into eight slits of 200 arcsec length by 0.05 arcsec width. In the second mode, a field of view of 40 arcsec^2 is redistributed into eight slits of 100 arcsec length by 0.05 arcsec width, which are duplicated by the beam splitter of a polarimeter coupled to the spectrograph.

Table 1. Requirements for the spectrograph design.

Detector format	4k × 4k
Pixel size	10 μm (visible), 20 μm (IR)
Total spectral resolving power	~ 300.000
Spatial resolution	0.01 arcsec (2 pixels)
Spectral range	3900-23000 Å
Number of simultaneous wavelengths	8 (5 visible and 3 IR)

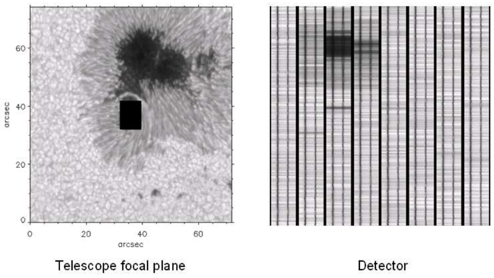

Fig. 1. The figure on the left shows the bidimensional entrance field of view for the integral field unit (indicated by the black rectangle), which is reorganized into eight slits. On the right, the simulated measurement with the detector is shown, used for the observation of the spectra associated to the eight slits. The spectral range for each slit on the detector is a function of wavelength.

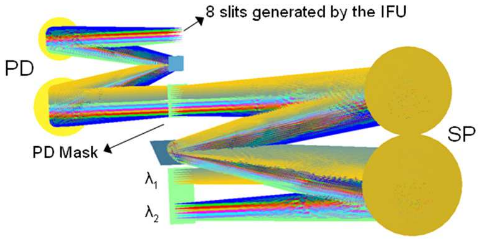

Fig. 2. Layout of the spectrograph coupled to the predisperser. The integral field unit (IFU) reorganizes the bidimensional field of view into the eight input slits for the predisperser (PD). At the predisperser image focal plane a mask selects the combination of wavelengths observed with the spectrograph (SP). At the spectrograph image focal plane, the spectra corresponding to the eight entrance slits are formed in each wavelength interval (centered around λ_1 and λ_2 in the example).

4. Image slicer

The integral field unit of this spectrograph is based on the image slicer concept. It is a compact, elegant and high efficiency alternative.

A new design of image slicer (Calcines et al. 2012b), called MuSICa (Multi-Slit Image slicer based on collimator-Camara), has been specifically developed for this instrument. In general, an image slicer reorganizes a bidimensional field of view into a long slit, and eight image slicers are needed to satisfy the multi-slit capability.

MuSICa has 3 arrays of mirrors: slicer, collimator and camera mirror arrays. The first array is composed by flat mirrors with a width of 50 μm and whose function is to cut the bidimensional entrance field of view. The sliced beams are sent to the collimator mirrors using X and Y axis tilts (Fig. 3 (a)). Collimator and camera mirrors are spherical and are distributed in 2 columns whose height is comparable to the generated slit height. This reduces the off-axis distances and improves the optical quality. Collimator mirrors collimate the beams and generate an image of the pupil between them and the camera mirrors. At that position a pupil mask is placed, to avoid the contribution of scattered light. Collimator and camera mirrors have an antisymmetric spatial distribution, with crossed correspondences of the beams. The pupils of the different beams are overlapped (see Fig. 3 (b)) and the mask has only one circular aperture. The symmetry of the design facilitates the manufacturing process, the alignment and reduces the costs. Camera mirrors focus the beams corresponding to different field points, one on top of others, generating the output slits (Fig. 3 (c)).

Table 2. Technical characteristics of the image slicer of EST.

MACRO-SLICER	
Entrance field of view	6.32 × 12.66 arcsec^2
Linear size of the array	6.128 mm ×12.275 mm
Input focal-ratio	F/50
Number of mirrors of the array	8
Curvature	Flat
Linear size of each mirror	0.766 mm × 12.275 mm
FoV per image slicer	0.79 × 12.66 arcsec^2
SLICER MIRROR ARRAY	
Number of mirrors	16
Curvature	Flat
Size of each mirror	0.049 mm × 12.275 mm
COLLIMATOR MIRROR ARRAY	
Number of mirrors	16
Curvature	Spherical
Focal length	220 mm
CAMERA MIRROR ARRAY	
Number of mirrors	16
Curvature	Spherical
Output focal-ratio	F/40
Focal length	176 mm

In the case of MuSICa, these mirrors also send the pupil to infinity and make the focal ratio conversion from the telescope F/50 to the spectrograph F/40. The ZEMAX optical design of MuSICa is presented in Fig. 4.

In order to generate the eight slits, the entrance field of view is cut, at the telescope focal plane, into eight sub-fields by an array of eight flat mirrors with different orientations called macro-slicer. Each sub-field is the input for an image slicer. Since macro-slicer and slicer mirror array are flat, they are combined into the same component. The eight arrays of slicer mirrors (one per image slicer) are integrated over their corresponding mirror of the macro-slicer. This combination minimizes the number of optical components used to reorganize a 2-D field of view into more than one slit.

The 80 arcsec^2 entrance field of view has been selected in a rectangular shape with 6.32 arcsec width by 12.66 arcsec length. The macro-slicer, placed at the F/50 telescope image focal plane, has the linear size of this field, 6.128 mm width by 12.275 mm length and its eight mirrors have a size of 0.766 mm by 12.275 mm (0.79 arcsec × 12.66 arcsec). The slicer mirror arrays cut their entrance sub-fields into slices of 0.05 arcsec width. This value is given by the required spectrograph input spatial sampling, 0.05 arcsec per slit width. The field of view and the size of the slices determine how many mirrors compose the different arrays, sixteen in this case. The slicer mirrors have a rectangular shape with a size of 0.049 mm width by 12.275 mm length. The focal length for the collimator mirrors is 220 mm and 176 mm for the camera mirrors. The aperture of the pupil mask has a diameter of 5 mm. The technical characteristics of the image slicer components are presented in Table 2 .

The same IFU is compatible with the two modes of operation of this instrument, illuminating it adequately in each case. The spectroscopic mode uses all the mirrors of

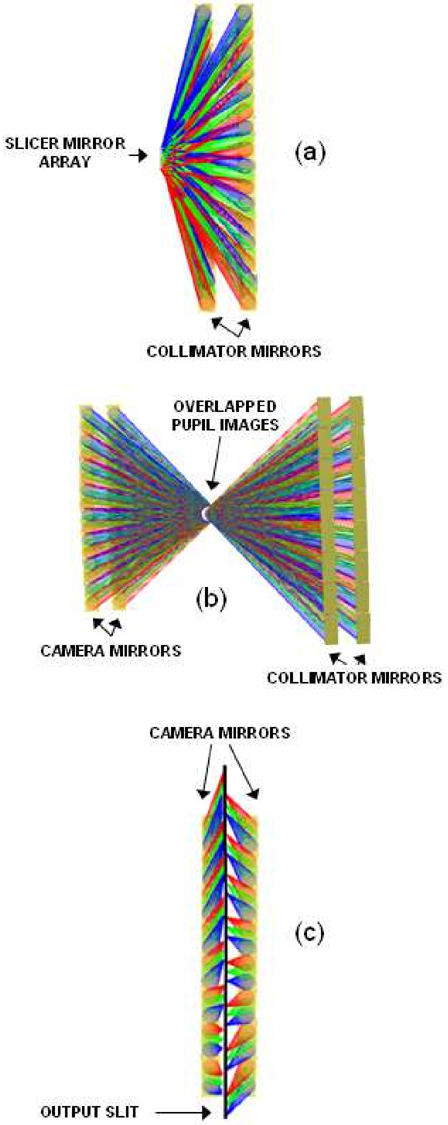

Fig. 3. MuSICa layout step by step. Figure (a) shows how the slicer mirrors send the sliced beams to the collimator mirrors. Figure (b) shows the optical path of the beams from the collimator mirrors to the camera mirrors. Collimator and camera mirrors have an antisymmetric spatial distribution with crossed correspondences of the beams. The pupil images associated to the different beams are overlapped. In figure (c) the camera mirrors focus the beams, one on top of others, alternating beams from each column, and generate the output slit.

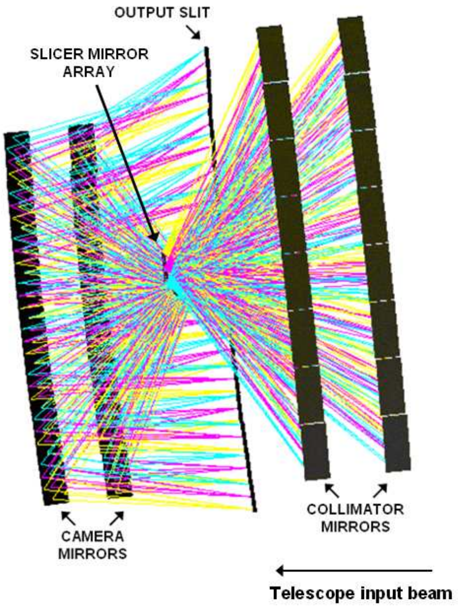

Fig. 4. ZEMAX optical design of the MuSICa image slicer. In the middle of the layout the slicer mirror array cuts the image into sixteen sub-beams. They are sent to the collimator mirrors using different orientations of the slicer mirrors. All sub-pupils are overlapped in a position very near to the slicer array. The camera mirrors focus the sub-beams and generate the output slit, sending the exit pupil to infinity.

the image slicer, sixteen per array, to generate 200 arcsec length slits. Only one half of them, eight per array, are needed for the spectro-polarimetric mode, for which the slits have 100 arcsec length. The central mirrors of each array, for which the off-axis distance is smaller and thus, the optical quality better, are used for this second mode.

Telecentricity is a very important condition for both the integral field unit and the spectrograph. Using an image slicer, the entrance field of view is sliced into several sub-beams, and a pupil image is got for each one of them. After the reorganization of the field into the slits, all these pupil images are again recomposed into one over the diffraction grating. Finally, the pupil is sent to the infinity and the detectors are illuminated homogeneously.

The optical quality of MuSICa is limited by diffraction.

5. Conclusions

The proposed spectrograph satisfies the requirements. It presents multi-slit and multi-wavelength capabilities, offering high resolution and an optical quality at diffraction limit. This instrument has been optimized for the study of the photosphere and chromosphere coupled to the 4-m European Solar Telescope.

A new concept of image slicer has been designed. It is a telecentric system, also diffraction limited and compatible with the 2 modes of operation of the spectrograph. The symmetry of its design facilitates the manufacturing process, the alignment and reduces the costs.

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