MEGARA: the future optical IFU and multi-object spectrograph for the 10.4m GTC Telescope

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ABSTRACT

In these proceedings we give a summary of the characteristics and current status of the MEGARA instrument, the future optical IFU and MOS for the 10.4-m Gran Telescopio Canarias (GTC). MEGARA is being built by a Consortium of public research institutions led by the Universidad Complutense de Madrid (UCM, Spain) that also includes INAOE (Mexico), IAA-CSIC (Spain) and UPM (Spain). The MEGARA IFU includes two different fiber bundles, one called LCB (Large Compact Bundle) with a field-of-view of 12.5×11.3 arcsec^2 and a spaxel size of 0.62 arcsec yielding spectral resolutions between R=6,800-17,000 and another one called SCB (Small Compact Bundle) covering 8.5×6.7 arcsec^2 with hexagonally-shaped and packed 0.42-arcsec spaxels and resolutions R=8,000-20,000. The MOS component allows observing up to 100 targets in 3.5×3.5 arcmin^2. Both the IFU bundles and the set of 100 robotic positioners of the MOS will be placed at one of the GTC Folded-Cass foci while the spectrographs (one in the case of the MEGARA-Basic concept) will be placed at the Nasmyth platform. On March 2012 MEGARA passed the Preliminary Design Review and its first light is expected to take place at the end of 2015.

Keywords: instrumentation: spectrographs, techniques: spectroscopic, galaxies: Local Group, spiral, kinematics and dynamics, ISM: kinematics and dynamics

1. INTRODUCTION

In October 2009, GRANTECAN, the public company responsible for the construction and management of the 10.4m GTC, published an *Announcement of Opportunity* for a second generation mid-resolution optical spectrograph. The UCM and its partners in the MEGARA Consortium answered that call and on September

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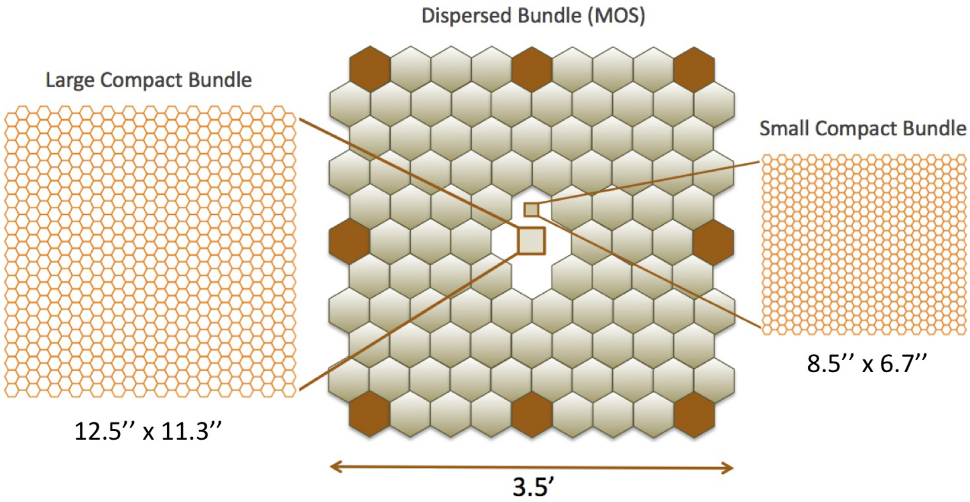

Figure 1. Layout of the MEGARA focal plane with the two IFU bundles in the center and the patrol areas of the hexagonally-packed 100 MOS positioners around them.

2010, after passing a competitive Conceptual Design Review, MEGARA was selected as the best alternative for the next visible mid-resolution spectrograph for the GTC. The Preliminary Design Review was passed on March 21^{st}-22^{nd} 2012.

MEGARA is an integral-field unit (IFU) and multi-object spectrograph (MOS) that is able to work in the entire optical window (between 3,700-9,800Å) at resolutions ranging from R(FWHM)$\sim$6,800 to 20,000. Two IFU bundles are available in MEGARA that can be used with any of the VPH disperser elements on the instrument. These two bundles cover 12.5×11.3 arcsec^2 on the sky with spaxel size of 0.62 arcsec (Large Compact Bundle; LCB) and 8.5×6.7 arcsec^2 with 0.42-arcsec spaxels (Small Compact Bundle; SCB). Regarding its MOS capabilities, MEGARA allows simultaneously observing 100 objects in a 3.5×3.5 arcmin^2 field of view (FoV; see Figure 1) and it is able to reconfigure the entire focal plane in less than 1 minute of time. That makes of MEGARA (in combination with GTC) an ideal instrument for observing even large areas of the sky where the density of targets (either because they are numerous or because very faint limiting magnitudes are aimed) approaches 5-10 arcmin^{-2} or even larger values.

In these proceedings we summarize the science drivers of the project (Section 2), the main characteristics of the instrument both at the Folded-Cass focal plane (Section 3) and at the Nasmyth platform (Section 4) and the status of the project (Section 5). More details on specific subsystems of the instrument can be found elsewhere in this volume[1,2,3,4,5].

2. SCIENCE DRIVERS

In this section we briefly summarize the scientific objectives that have driven the design of MEGARA and that have been put together by the MEGARA Science Team. The scientific interests of the MEGARA Science Team can be grouped in two categories, (1) the study of Galactic and extragalactic nebulae and (2) the study of point sources (or close to point sources) with intermediate-to-high surface densities. Among the former our interests include the study of Planetary Nebulae, nearby galaxies, and the high-redshift intergalactic medium (IGM) and among the latter Galactic open stellar clusters, resolved stellar populations in Local Group galaxies, intermediate-redshift dwarf and starburst galaxies, and high-redshift cluster galaxies are the main subject of our research activities. The MEGARA Science Team encompasses researchers with a broad range of scientific interests belonging to institutions of all members of the GTC Consortium (Spain, Mexico and University of Florida). This guarantees that, as a facility instrument, MEGARA will also successfully serve to the interests of the members of the GTC astronomical community and their collaborators.

What is common to all our scientific interests with the MEGARA Science Team is the need for an intermediate-to-high spectral resolution, in the range R = 6,000 - 20,000. In some cases this need is a mere consequence of velocity resolution (kinematics) but in many cases is given by the need of reducing line blending, either directly when lines from different elements ought to be measured in stars or via a reduction in the degeneracy of the properties of composite stellar populations.

Below we describe in more detail one of the science interests, the most ambitious one in terms of the observing time required. For more information on this or other topics of interests that we as Science Team plan to address with MEGARA the reader is referred to the project webpage[6] and to the documents posted there.

2.1 MEGARA Galaxy Disks Evolution Survey

The MEGARA Galaxy Disks Evolution Survey (MEGADES hereafter) is an attempt to shed light on the evolution* of galaxy disks by looking into the detailed information contained in the stellar populations, stellar and gas kinematics, and stellar and ionized-gas chemical abundances.

The evolution of galaxies (including disk galaxies) is a complex process as many are the mechanisms that might alter their present-day photometric, chemical, and kinematical properties: monolithic collapse, major and minor mergers, bars, rings, density waves, stellar diffusion, gas in-fall, and, in the case of galaxies in clusters, also ram pressure striping and galaxy harassment[8]. Despite this rather discouraging scenario, in the case of the formation of the disks in galaxies a picture has emerged in recent years that attempts to explain most of their observational properties: During the first several Gyr of history ($z>1$) and possibly following some level of monolithic collapse the evolution of disk galaxies is dominated by frequent (mostly minor) mergers, which lead to the formation of what it is known as the thick-disk component. After that period the frequency of mergers decreases and the disk becomes dynamically cooler allowing for the formation of the so-called thin-disk component. During the evolution of the thin disk (at $z<1$) the high angular momentum of the gas in the outer parts of the disks results in a delayed gas in-fall and star formation activity in these regions compared to the inner disk. This is known as the *inside-out* formation scenario for galaxy disks.

While the inside-out scenario has served to successfully reproduce many of the observational properties of galaxy disks, mainly coarse properties, such as color and metallicity gradients, and restricted to a specific radial range within galaxies, there is cumulative evidence that such scenario cannot predict neither the details of these properties (in terms of spatial resolution, chemical abundances and certainly kinematics) nor even coarse properties across the entire face of the disks. In this regard, significant departures from the predictions are found in many objects both in the inner and very outer parts:

- The analysis of a large sample of spiral disks observed as part of the Sloan Digital Sky Survey (SDSS)[10] have revealed U-shaped color profiles near the position where the galaxy surface brightness decreases abruptly. This work demonstrated that while in the inner disk the profiles show the expected bluing towards the outer regions, this trend reverses as we move beyond the break in surface brightness.
- The inside-out scenario predicts a roughly constant negative gradient throughout the entire galaxy disk. The analysis of the outer disks of M33, NGC 300, or M83 among others, however, indicate a flattening or even a reversal in the metal abundance gradient (either of the stars or the ionized gas) that cannot be explained by a simple inside-out growth model[11,12,13,14].
- In our own Milky Way, the simple inside-out scenario has also failed to explain the shape of the age-metallicity distribution of stars in the Solar neighborhood, the dispersion in age predicted at a given metal abundance being significantly narrower than that observed[15].
- Muñoz-Mateos et al.[16] showed that in the inner disks, where one would expect a negative gradient in color (or equivalently in age or specific SFR; sSFR) galaxies show a large dispersion in sSFR gradient with many galaxies showing null or even negative sSFR gradients. In this same sense, some N-body simulated disks[17] seem to have formed outside-in.

* "Evolution" here has a very broad meaning as it refers to all photometric, chemical and kinematical evolution, as originally formulated by B. Tinsley[7].

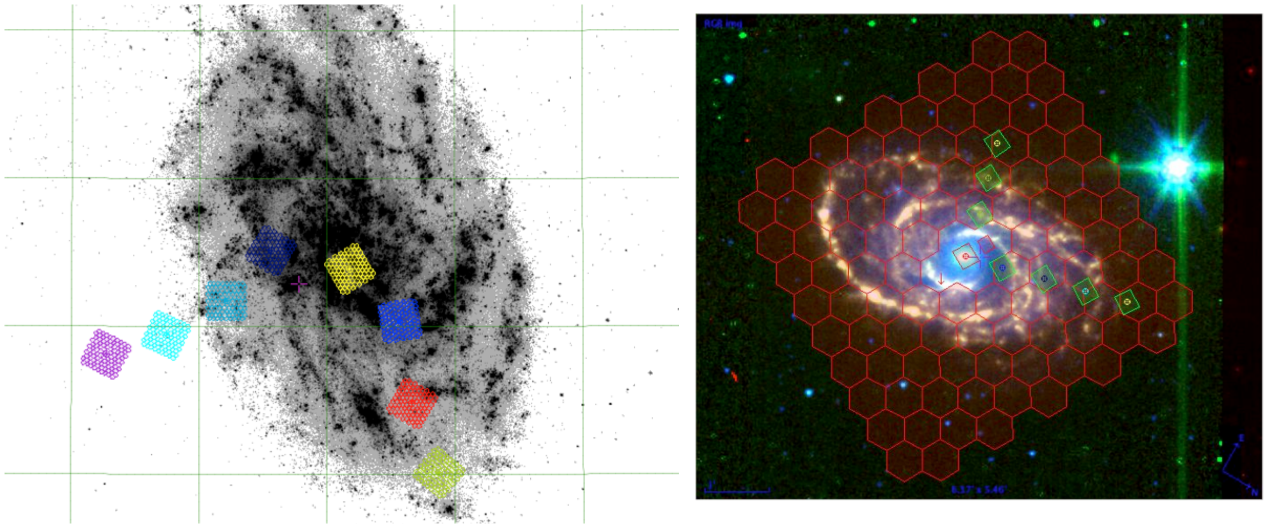

Figure 2. (Left:) Layout of the proposed MEGADES MOS fields on the disk of M33 (the GALEX NUV image of M33 is shown in the background[9]). All except one pointing (in cyan) coincide in position, field-of-view (FoV) and orientation with observations obtained with ACS/HST in at least two bands, F606W and F814W. These will be used to identify potential spectroscopic blends. (Right:) False-color IRAC image of the MEGADES-S4G galaxy NGC 5371 with the footprint of the central MEGARA IFU+MOS pointing (in red) and the major and minor-axes IFU pointings (in green) over-plotted. The instrument position angle has been changed for an optimal use of the instrument. Note that the inclination angle of the target allows for a proper derivation of the galaxy velocity ellipsoid. In highly face-on systems only the central pointing will be obtained.

- Internal secular processes such as gas inflow through a bar, bar dilution, and star formation in rings that shrink in radius with time can form inner disks[18,19,20] but they can be also induced externally to the galaxy. Minor mergers can structurally transform a Sb or Sc galaxy into a S0, generating inner disks and rings in the remnant through the coupling of the satellite disruption with the evolution driven by transient spirals and bars induced by the merger[21,22].
- Finally, episodes of intense nuclear (AGN) or star-formation activity can also have a profound impact on the (photometric and chemical but also, indirectly, kinematical; e.g. through bar destruction) evolution of disks[23]. We could not even rule out that some disks might have actually gone through a major merger phase in the past and re-grow a disk since then[24].

While the Gaia mission will put this scenario of inside-out formation of disks to test in the case of our own Milky Way, very few coordinated efforts (neither ambitious) are being put together to analyze this topic in the necessary detail in other Local Group disks or beyond (a notorious exception being the SPLASH survey on M31[25]). MEGADES emerges with the objective of determining the relative role of in-situ star formation, stellar migration, satellite accretion and (minor-)merging among others in the evolution of galaxy disks. The results described above have recently demonstrated that the naive picture of in-situ-dominated evolution provided by the inside-out scenario should be refined, at least in a fraction but perhaps in all external disk galaxies.

MEGADES is based on a two-tiered strategy that aims at obtaining mid-to-high-resolution spectra of (1) resolved stellar populations (mainly RGB stars and massive blue stars) in Local Group galaxies and (2) the unresolved light from a complete sample of disks beyond the Local Group (extracted from the magnitude- and volume-limited S4G sample[26]).

In the former case we will mainly focus on M33 as it has the right inclination to measure its velocity ellipsoid by means of major and minor-axis scans and to avoid significant dust-obscuration effects. Due to its proximity we can aim to obtain spectroscopy of giant stars up to 1 mag below the tip of the RGB (see left panel of Figure 2). Observations with the MEGARA IFU will also allow deriving detailed chemical abundances of individual HII regions at different radii (including NGC 604) using both collisionally-excited lines (CELs) and recombination lines (RLs). Thus, MEGADES will produce the most comprehensive dataset on the study of ionized-gas and single-star kinematics and chemical abundances in a Local Group galaxy beyond the Milky Way. This will be the first necessary ingredient to determine the relative role of in-situ star formation, stellar migration, minor merging, etc. on the evolution of disks other than ours.

However, the study of the role of all these processes and of the possible failures of the inside-out scenario for the evolution of disks should not be restricted to a few Local Group disks and it has to be necessarily complemented with the analysis of a large (complete) sample of nearby disk galaxies. In this regard, we plan to analyze multiple (light-weighted) spectral features and associated kinematics (including the velocity ellipsoid) of both gas and stars as a function of galactocentric distance for a sample of disks extracted from the *Spitzer Survey of Stellar Structure of Galaxies* (S4G[26]). This will provide the necessary information (complementary to that on M33) to analyze the impact of stellar migration, satellite accretion and minor merging as a function of galaxy type and environment. The observation of this sample with MEGARA at GTC will also provide the necessary dataset to analyze the formation of inner disks and the frequency and potential impact of nuclear and active star formation activity on the evolution of disks as a whole (see right panel of Figure 2), again, with an unprecedented combination of spectral resolution and depth.

3. MEGARA FOLDED-CASS SUBSYSTEMS

The MEGARA Folded Cassegrain subsystems include all components that collect and conduct the light from the Folded-Cass focal plane to the spectrograph on the Nasmyth platform. Those elements: (i) the Field Lens to correct from lack of telecentricity providing a telecentric focal plane for the IFU bundles and the every MOS microlens array (b) the microlenses that change the focal number of the telescope allowing a good coupling with fibers, (c) the fiber bundles, (d) the Fiber MOS that allows to position up to 100 minibundles in a dedicated area of the focal plane, (e) the interface plate that supports the LCB and SBC IFUs in the central area of the focal plane, (f) the Folded-Cass Rotator Adapter that provides the interface with the rotator at GTC (the F-C rotator has been already delivered to GTC) and (g) the pseudo-slit plate that positions the fibers at the entrance of the spectrograph following the slit curvature obtained from the optimization of the spectrograph optical design.

Since there is already a communication[4] on this issue in this same volume we refer the reader to it for more details on the MEGARA Folded-Cass subsystems.

4. MEGARA SPECTROGRAPH(S)

Regarding the MEGARA spectrograph we should first mention that the funding from GRANTECAN (plus the MEGARA Consortium in-kind resources) cover all steps until the delivery of the instrument to GTC (detailed design, construction, AIV and commisioning) for all Folded-Cass subsystems and one single spectrograph. This MEGARA-Basic concept would imply that only one of the three fiber bundles arriving to the Nasmyth platform (namely the SCB and LCB IFUs and the Fiber MOS) could be used simultaneously. However, the MEGARA Consortium is still working on the possibility, only limited by the potential availability of funds at this stage, that a second spectrograph could be built (MEGARA-Advanced) that woud allow using one of the IFU bundles and the MOS simultaneously.

The MEGARA spectrograph(s) are expected to be located at either the Nasmyth platform of GTC or on a Nasmyth-like platform locate below the Nasmyth one. GRANTECAN is actively working on providing the MEGARA team with the final location for this major part of the instrument so to close all interfases with the telescope as soon as possible.

The spectrograph in MEGARA is a fully refractive optical system. It is composed by a pseudo-slit, where fibers are placed simulating a long slit 119mm in length with a RoC of 1075mm. In the case of MEGARA-Basic a mechanism will exchange the pseudo-slit in place for the LCB IFU, SCB IFU and MOS modes respectively. This, a XY mechanism, will also act as focussing mechanism for the spectrograph. Obviously, as the LCB and MOS use 100-micron-core fibers the spectral resolutions achievable (see the VPH parameters listed in Table 1) are lower than those to be obtained with the 70-micron-core fibers in the SCB. The difference between the two is approximately 20%, which is smaller than one would expect based on fiber-core size arguments only. This is

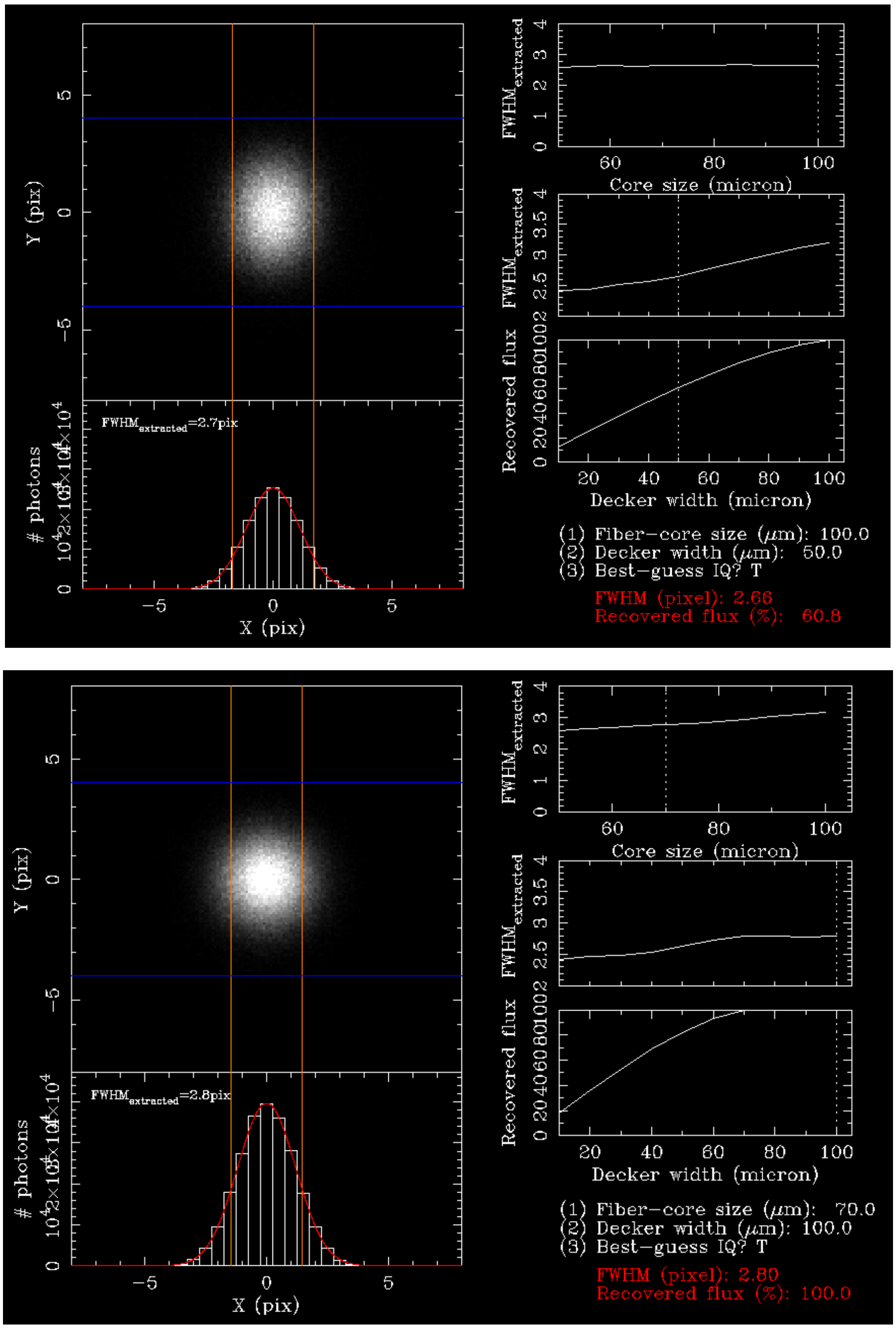

Figure 3. (Top:) Monte Carlo simulation of the light distribution of an unresolved spectral line on the detector in 2D (but with a high spatial sampling; top-left panel) and the same distribution collapsed in the spatial direction and projected onto 15-micron-wide spectral pixels (bottom-left panel). This plot shows the case of an observation with a 100-micron-core fiber and a 50micron-wide decker. The plots at the right show how the FWHM of the extracted (unresolved) spectral line would change with the core size for a fixed decker width (right-top panel) and how this and the fraction of flux recovered (i.e. not lost at the decker) would change as a function of decker width but for a fixed fiber core size (middle- and bottom-top panels). (Bottom:) Same thing as above but for the case of 70-micron-core fibers with an open decker. Note that now the flux recovered is 100% for roughly the same spectra resolution. The use of the decker could be an advantage in the case of MOS when spectral resolutions of the order of R$\sim$15,000-20,000 are needed but not that much when one of the MEGARA IFU is planned to be used.

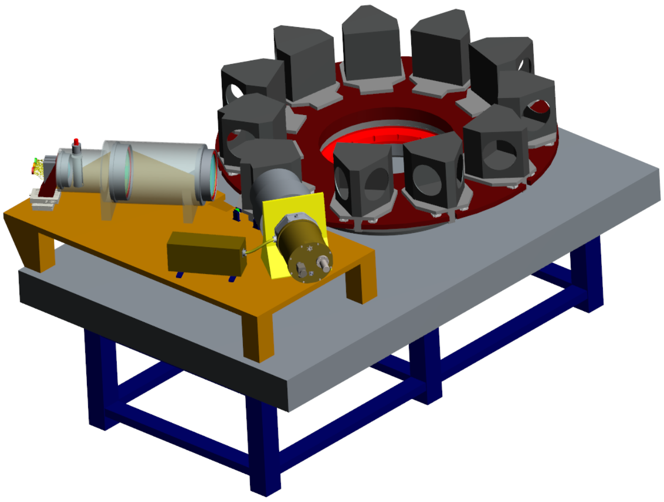

Figure 4. View of the 3D mechanical design of the MEGARA spectrograph[3].

due to the fact that with 70-micron-core fibers we are already at the limit of our best estimate for the image quality of the spectrograph (full error budget included). However, as a conclusion from the Preliminary Design Review, we incorporated in the design of MEGARA the possibility of putting a decker plate that when closed to a width of 50micron would yield a spectral resolution with the 100-micron-core fibers comparable to that to be obtained with the SCB without any decker. Note that because the light distribution coming from the optical fibers at the slit is roughly an homogeneous circle (but not a rectangle, like in a standard long-slit spectrograph), the increase in resolution by closing a (rectangular) decker is not equivalent to reducing the size of the diameter of the fibers by the same amount (see Figure 3).

Following the light path after the pseudo-slit and the decker we find then the collimator, which is composed by 5 lenses (1 singlet and two doublets). The first lens of the collimator is the only aspherical surface of the instrument, which also one of the smallest lenses in the system (140mm diameter). A slit shutter is placed right beyond the first collimator lens. The pupil has 160mm free diameter and it is the location for the VPH-gratings. The order-sorting filter will be mounted when needed together with the grating in the opto-mechanical mount (only four gratings need an order-sorting filter). A total of 11 VPHs can be simultaneously mounted on the VPH wheel, which allows providing full optical coverage at low+mid resolutions (R$\sim$6,800-12,000) or mid+high resolutions (R$\sim$12,000-20,000). Once the beam passes through the grating it goes to the camera (composed by two doublets and 3 singlets, being the last lens also the cryostat window) and focuses on the detector, which is inside a liquid nitrogen open-cycle cryostat. In Figure 4 we show a view of the mechanical design of the spectrograph.

Since the MEGARA spectrograph optical and mechanical design and the cryostat are described in detail in this volume[1,2,3] we refer the reader to these communications for further details.

5. STATUS OF THE INSTRUMENT

The Preliminary Design Review of the instrument took place in Madrid on March 21st-22nd 2012. As a consequence of it the MEGARA team has recently incorporated a few minor changes to the design (mainly the possibility of having a decker and the focus mechanism on the pseudo-slit). This design will then go through a Critical Design Review at the beginning of 2013 after which we will start with the construction of the different subsystems. Some of the subsystems (Fiber MOS, VPH Wheel) will actually go through CDR by the end of this year 2012 already. The First Light of the instrument at GTC is expected to the take place at the end of 2015.

Table 1. Parameters of the different VPHs designed for MEGARA. The spectral ranges, including the central wavelengths, are valid for all LCB, SCB and MOS modes independently of decker width. Spectral resolutions listed are for the 100-micron-core fibers of the LCB and MOS modes; spectral resolutions are increased by ∼20% when either the 70-micron-core fibers of the SCB or a 50-micron-wide decker in combination with the 100-micron-core fibers are used (see Figure 3).

VPH Name	Setup	R(FWHM)	$\lambda_1 - \lambda_2$ (Å)	λ_c (Å)	$\Delta\lambda$(FWHM)† (Å)	Δv(FWHM) † (km/s)	lin res (Å/pix)
VPH405-LR	LR-U	6,836	3,670 - 4,402	4,051	0.593	44	0.185
VPH480-LR	LR-B	6,836	4,348 - 5,216	4,800	0.702	44	0.219
VPH570-LR	LR-V	6,836	5,164 - 6,194	5,700	0.834	44	0.261
VPH675-LR	LR-R	6,836	6,115 - 7,334	6,749	0.987	44	0.309
VPH865-LR	LR-I	6,836	7,836 - 9,399	8,650	1.265	44	0.396
VPH410-MR	MR-U	12,100	3,890 - 4,309	4,104	0.339	25	0.106
VPH443-MR	MR-UB	12,100	4,200 - 4,652	4,431	0.366	25	0.114
VPH481-MR	MR-B	12,100	4,562 - 5,054	4,814	0.398	25	0.124
VPH521-MR	MR-G	12,100	4,941 - 5,472	5,213	0.431	25	0.135
VPH567-MR	MR-V	12,100	5,371 - 5,950	5,667	0.468	25	0.146
VPH617-MR	MR-VR	12,100	5,847 - 6,477	6,170	0.510	25	0.159
VPH712-MR	MR-R	12,100	6,744 - 7,470	7,115	0.588	25	0.184
VPH777-MR	MR-I	12,100	7,362 - 8,154	7,767	0.642	25	0.201
VPH926-MR	MR-Z	12,100	8,778 - 9,723	9,262	0.765	25	0.239
VPH665-HR	HR-R	16,875	6,394 - 6,898	6,646	0.394	18	0.123
VPH863-HR	HR-I	16,875	8,306 - 8,961	8,634	0.512	18	0.160

†Computed at λ_c.

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