CARMENES. II: Optical and Opto-Mechanical Design

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ABSTRACT

CARMENES is a fiber-fed high-resolution échelle spectrograph for the Calar Alto 3.5m telescope. The instrument is built by a German-Spanish consortium under the lead of the Landessternwarte Heidelberg. The search for planets around M dwarfs with a radial velocity accuracy of 1 m/s is the main focus of the planned science. Two channels, one for the visible, another for the near-infrared, will allow observations in the complete wavelength range from 550 to 1700 nm. To ensure the stability, the instrument is working in vacuum in a thermally controlled environment. The optical design of both channels of the instrument and the front-end, as well as the opto-mechanical design, are described.

Keywords: Instrumentation, optical design, spectrograph, échelle, optical fibres, near-infrared, visible, radial velocity, exoplanets, CARMENES

1. INTRODUCTION

The overall aim of the CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Échelle Spectrographs; `http://carmenes.caha.es`) instrument is to perform high-precision measurements of stellar radial velocities with long-term stability. As most of the prospective exercises on exoplanet search have identified near-infrared as a key area for new development, the fundamental science objective is to carry out a survey of late-type main sequence stars with the goal of detecting low-mass planets. The precision of 1 m/s per measurement will permit to attain this goal.

CARMENES (Quirrenbach et al. 2010, 2012) consists of two channels to cover the complete wavelength range: a visible (VIS) part covering from 550 to 950-1050 nm and a near-infrared (NIR) one working between 950 and 1700 nm. Each channel is a complete spectrograph in a thermally stabilized vacuum vessel at a pressure of about 10^{-5} mbar. The VIS spectrograph works at room temperature (~12°C), the NIR one at ~140 K. The thermal stabilization will be within 0.01K. The spectrographs will be placed in the coudé room of the 3.5 m telescope at the Calar Alto Observatory, Almería, Spain, with a fiber-link to the front-end at the telescope.

The optical design of the instrument is based on the FEROS design (Kaufer 1997), being a grism cross-dispersed, white-pupil, échelle spectrograph working in quasi-Littrow mode using a two-beam, two-slice, image slicer. The resolving power is 82000 per sampling element with a mean sampling of 2.8 pix. The peak efficiencies of the instrument, including atmosphere, telescope and fiber link, will be 10% (VIS) and 13% (NIR).

Two fibers are contained in each fiber head and fed to the spectrographs. Using a 100 µm fiber, the entrance aperture on sky is 1.5 arcsec. In order to maintain the requested scrambling factor of at least 1000, the default solution is to use a

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classical double image scrambler. A detailed investigation has been started to replace this by non-circular (octagonal) fibers to allow for a higher overall throughput.

The front-end of the instrument will be attached to the Cassegrain focus of the Calar Alto 3.5m telescope. It includes a pick-up mirror, atmospheric dispersion corrector, dichroic beam-splitter, fiber heads for VIS and NIR and a guiding system.

An optimized calibration unit for each channel will be located in the coudé room with a fiber link to the front-end. The basic calibration mode is taking wavelength calibration parallel to the on-sky object integration through the second fiber. For faint stars, the second fiber can be used for sky-background determination while calibrating during the day; this mode will only be used after the necessary instrument stability is proved

The instrument optics final design review has just been passed. The complete instrument final design review is planned for the end of this year (2012). Installation at the observatory and commissioning will take place in early 2014. The science observations will start the around mid of 2014.

2. OPTICAL DESIGN

The optical design of the VIS channel spectrograph is shown in Fig. 1. Light from the telescope enters via two fibers (object and calibration/sky) at the position 'Fiber Exit'. An FN system converts the *f*/3.5 output from the fiber(s) to *f*/10 for the spectrographs. The image slicer is located at the intermediate focus, acting as the effective input 'slit'. A first pass of the collimator produces a 154 mm parallel beam. The échelle grating is slightly tilted perpendicular to the dispersion direction to separate the incoming and diffracted beam. A second pass of the collimator produces an intermediate spectrum on the folding mirror. The light passes the collimator a third time. The cross-disperser grism is located at the re-imaged (tilted) pupil of the system. The dioptric camera images the cross-dispersed spectrum onto the detector.

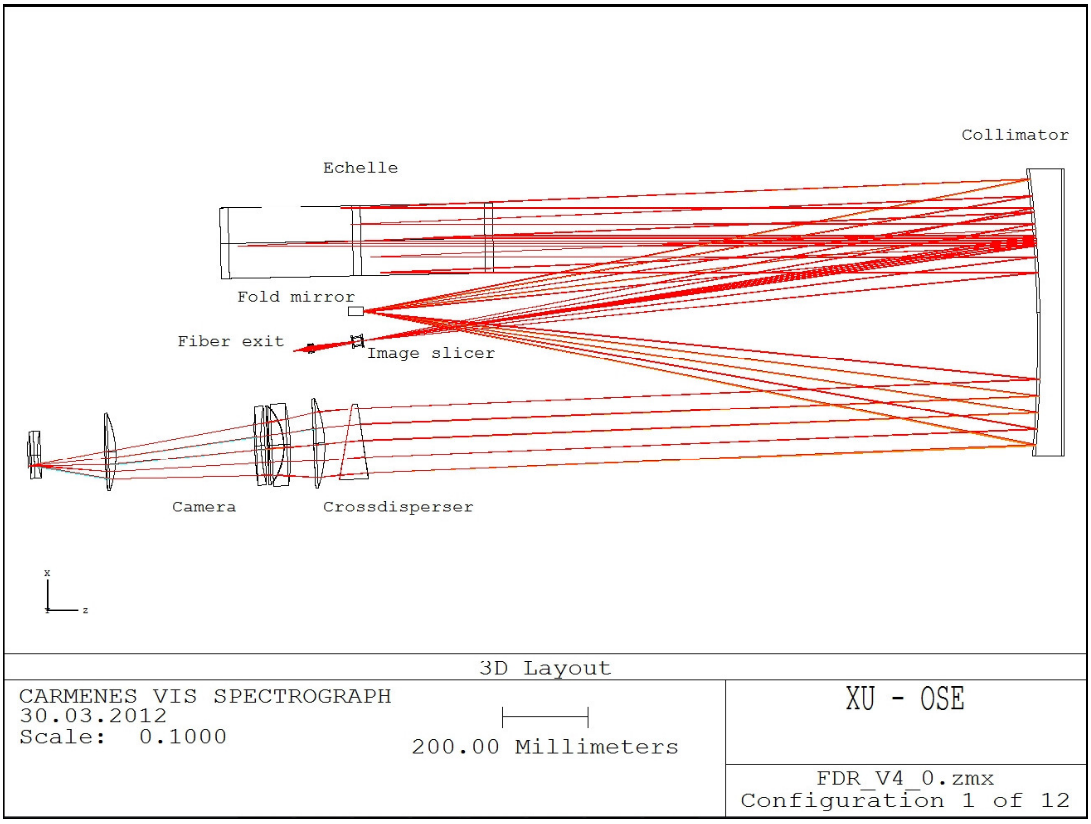


Figure 1.: Optical layout of the CARMENES spectrograph (VIS channel).

Both channels vary only slightly in their design by using the same type of échelle grating. The differences are the refractive components, namely the FN-system, cross-disperser and camera. In Table 1, the system data for both channels are summarized.

	NIR	VIS
Wavelength range	950-1700 nm (29 orders)	550-1050 nm (53 orders)
Resolving power	$\lambda/\Delta\lambda = 82000$	
Resolution element	2.8 pixels at the center of the detector (>2.3 pixels)	
Inter-fibre spacing	7 pixels	
Inter-order spacing	7 pixels (minimum)	
Entrance aperture on sky	1.50 arcsec	
Fibre input focal ratio	*f*/3.9	
Fibre output focal ratio	*f*/3.5	
Spectrograph beam size	153.3 mm	154.8 mm
Off-axis collimator	*f*/10.218	*f*/10.274
Échelle grating	RGL-Newport 53B..174E mosaic, R4, 75.2 deg, 31.6 grooves/mm, 154 mm x 596 mm	
Cross-disperser grism	Infrasil 13.85 deg apex angle, 81 grooves/mm	LF5 17.8 deg apex angle, 223 grooves/mm
Refractive camera		
f/#	*f*/3.53	*f*/2.94
Focal Length	548 mm	455 mm
Detector	Hawaii-2RG mosaic (× 2) 4096 x 2048 pixels 18 µm/pix 2.5 µm cut-off	CCD EEV 231-84 4096 x 4096 pixels 15 µm/pix
Operating Temperature	140 K	285 K

Table 1. Overview of the system data for the NIR and the VIS channels.

2.1 Fiber-entrance unit

The *f*/10 beam coming from the telescope is fed into the fibers with 100 µm diameter via a micro lens at *f* /3.9. The light emerges from the fibers at *f* /3.5 to keep the focal ratio degradation in the order of <10%.

Fig. 2 shows the spectrographs fiber entrance unit: the fiber exit is located at the left side and the fiber is re-imaged via a so-called FN system. The two-beam, two-slice image slicer is positioned at the re-image. A view of the sliced beams inside the slicer is shown in Fig. 3

The design of the two-beam, two-slice image slicer is based on the design and our experience of the ESO FEROS instrument (Kaufer 1998).

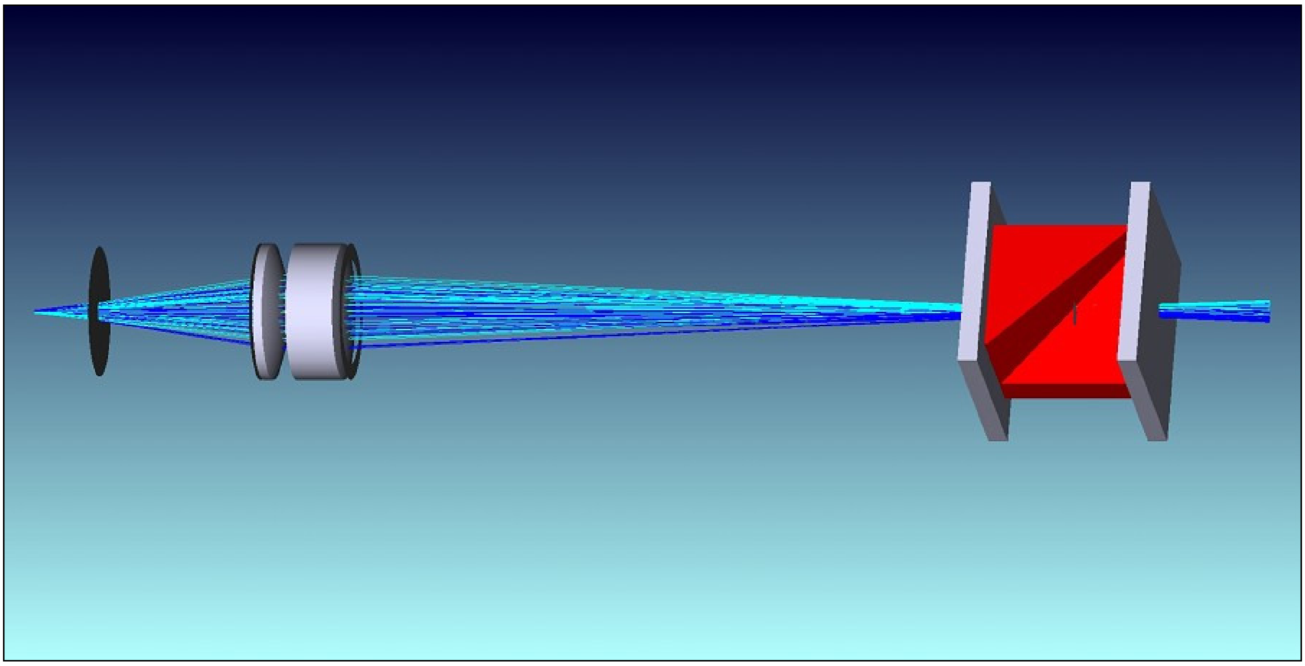
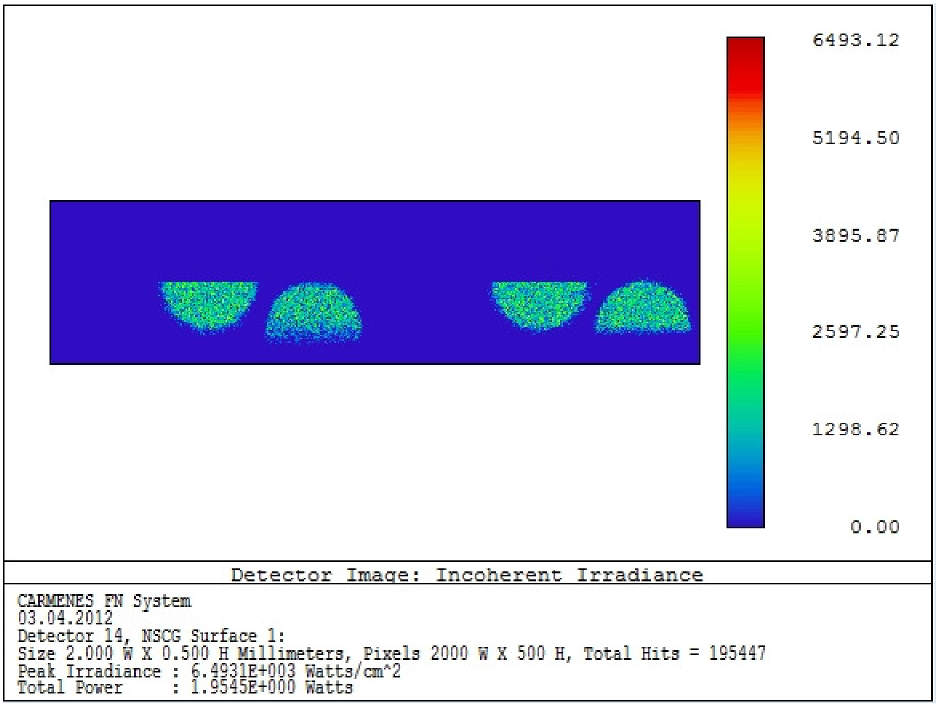


Figure 2.: 3D view of the fiber exit unit, including the pupil stop, the FN system and the image slicer.



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Detector Image: Incoherent Irradiance
CARMENES FN System
03.04.2012
Detector 14, NSCG Surface 1:
Size 2.000 W X 0.500 H Millimeters, Pixels 2000 W X 500 H, Total Hits = 195447
Peak Irradiance : 6.4931E+003 Watts/cm^2
Total Power     : 1.9545E+000 Watts
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Figure 3.: Image of the sliced images of the two fibers just inside the image slicer.

2.2 Collimator

For the collimator we choose a monolithic design cut from a large parent paraboloid with ~850 mm in diameter. This ensures ease of the initial alignment of the instrument as well as maximum stability against any thermal variations.

For the VIS channel, the collimator substrate is fused silica. For the NIR collimator, aluminun 6061-T6 is used to minimize the instrument re-adjustment needed during cooling down to the operation temperature of 140 K.

The reflective coating will be an enhanced silver coating for the VIS and a protected gold coating for the NIR channel.

2.3 Échelle

The échelle gratings of both channels are mosaics made using the master RGL-Newport 53B..174E. See Fig. 4 for the layout of the grating and its used area.

Even though this is nominally an R4, the effective blaze angle is around 75.4 deg. A working angle of 75.2 deg has been used for the optical layout in order to fulfill the resolution requirement and to place the blaze centrally on the detector.

The reflective coating is chrome-linked gold coating for both channels. The efficiencies measured on a test sample will be >60% over the full wavelength range of both channels with a peak around 70%.

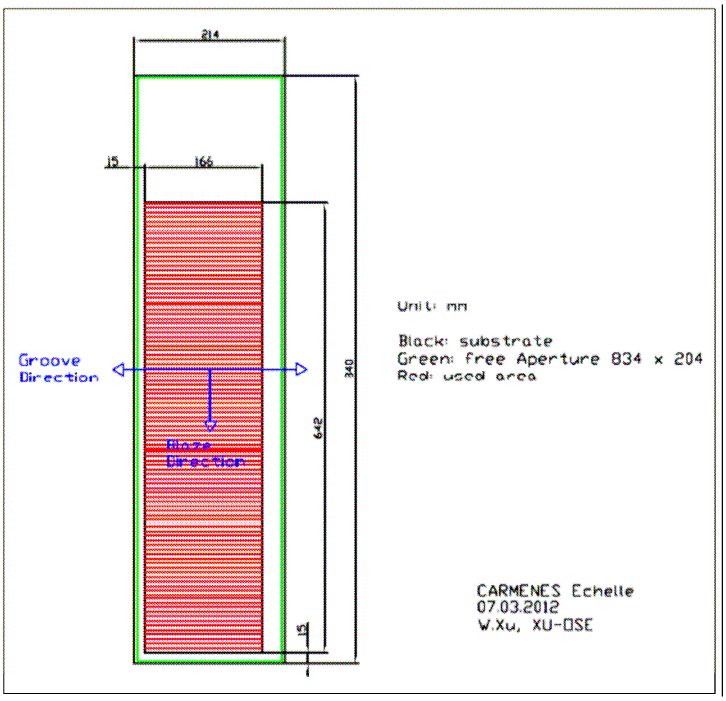

Figure 4.: Layout and used area of the échelle grating.

2.4 Cross-disperser grism

Both channels use conventional grisms as cross-disperser. The VIS channel uses LF5 as substrate together with a custom-made RGL-Newport grating with 223 lines/mm blazed at 700 nm. In the NIR, the prism substrate is Infrasil with a custom grating with 81 lines/mm blazed at 1150 nm.

Special care has been taken for the design of the camera tube in order to effectively suppress the zero order from the grating to reach the detector.

2.5 Camera

A dioptric design has been chosen for the cameras of both channels. All lenses are air-spaced as the instrument is working in vacuum and, in the case of the NIR channel, at low temperatures.

The VIS camera consists of seven lenses in four groups. The field lens acts as an entrance window to the detector dewar. Its last surface is cylindrical. The clearance is 5 mm. The layout is shown in the following Fig. 5. The NIR camera consists of five lenses in three groups plus a flat detector cryostat window. One of the lens surfaces is aspherical with a conic constant of –1.

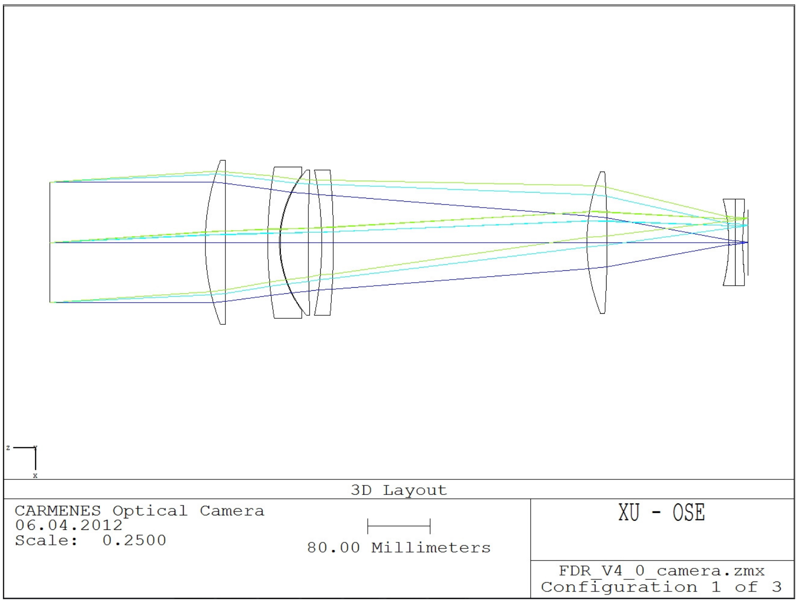

Figure 5.: Layout of the camera for the VIS channel.

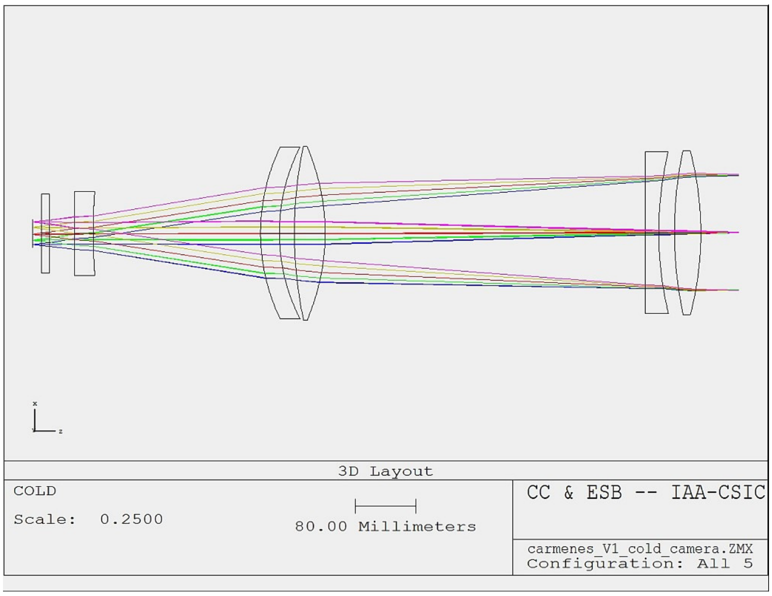

Figure 6.: Layout of the camera for the NIR channel.

3. OPTO-MECHANICS

The main criteria for the opto-mechanical design have been to reach the maximum stability, thermal and structural, and to find a solution that can be used for both channels of the instrument with minor or no modifications at all.

Both channels are placed inside a vacuum vessel each. The vacuum vessels will operate at a pressure of $\sim 10^{-5}$ mbar and thus eliminate all effects on instrumental stability from pressure variations and possible convection effect. The required temperature stability is ±0.01 K during a night and <±0.1 K on long-term. This is reached by (a) enclosing the vessels in temperature stabilized rooms (±0.5 K) and (b) an effective shielding of the spectrographs. In the case of the VIS channel, the temperature stabilization is done by the thermal chamber without any active control inside the vessel. For the NIR spectrograph, a special cooling unit is used for the cool-down and stabilization at the operating temperature of 140 K (Becerril et al. 2012). Fig. 7 shows the general view of the NIR optical bench and its shield with the heat exchangers for the thermal control.

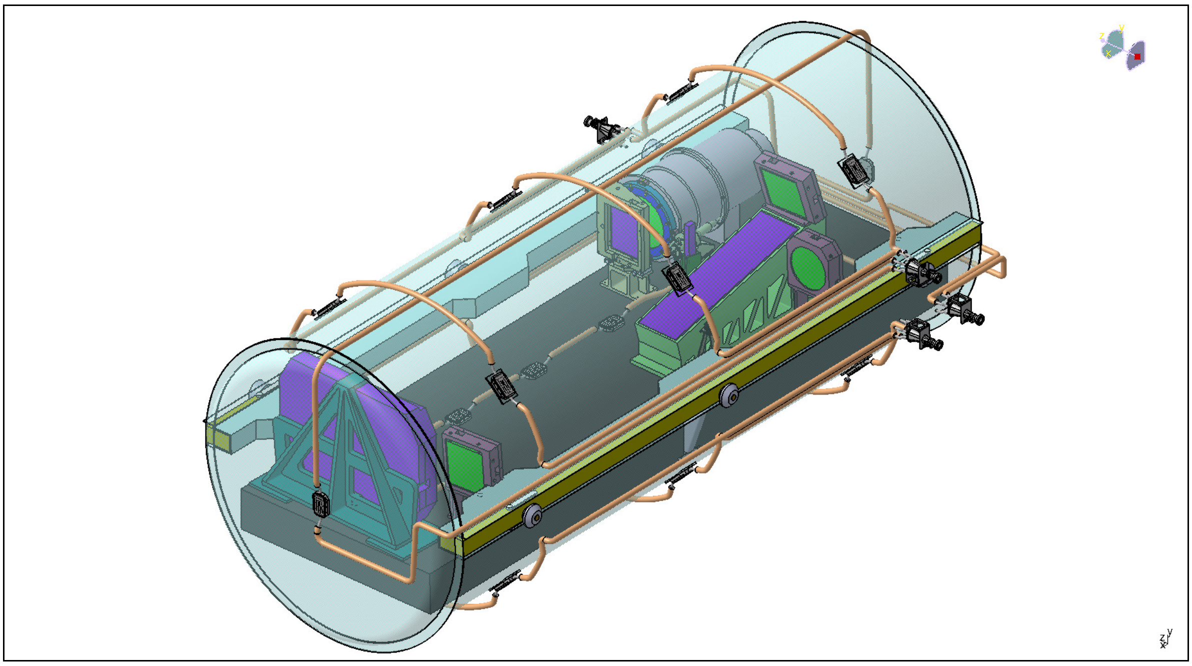

Figure 7.: General view of the fully assembled CARMENES NIR optical bench.

The mechanical link of the optical benches to the vacuum vessels is implemented by means of two long beams (yellow colored in the Fig. 7) that, in their turn, are attached to respective rails through several wheels. Three highly insulating parts provide the attachment of the optical bench to the long beam. In this way, the conductive losses incoming to the bench are negligible. The cross section of the insulating parts has been minimized to provide higher insulation while still keeping the structural performance. At the same time, the length of those parts has been maximized for thermal purposes.

The optical benches will be inserted into and removed from the vacuum vessels by rails. The benches can be extracted by about 0.5 m; for complete removal, they will be attached to a support carriage that, in its turn, includes rails as well. In Fig. 8, a vacuum vessel with the optical bench partially retracted and opened shield is shown. This position allows access to the fiber exit unit and the detector cryostat and is used during fine alignment at the observatory. The size of the vessel is 1.7 m diameter and 2.7 m total length. This solution has been chosen to ensure the proper handling of the heavy assembly composed by the optical bench and all the opto-mechanical packages.

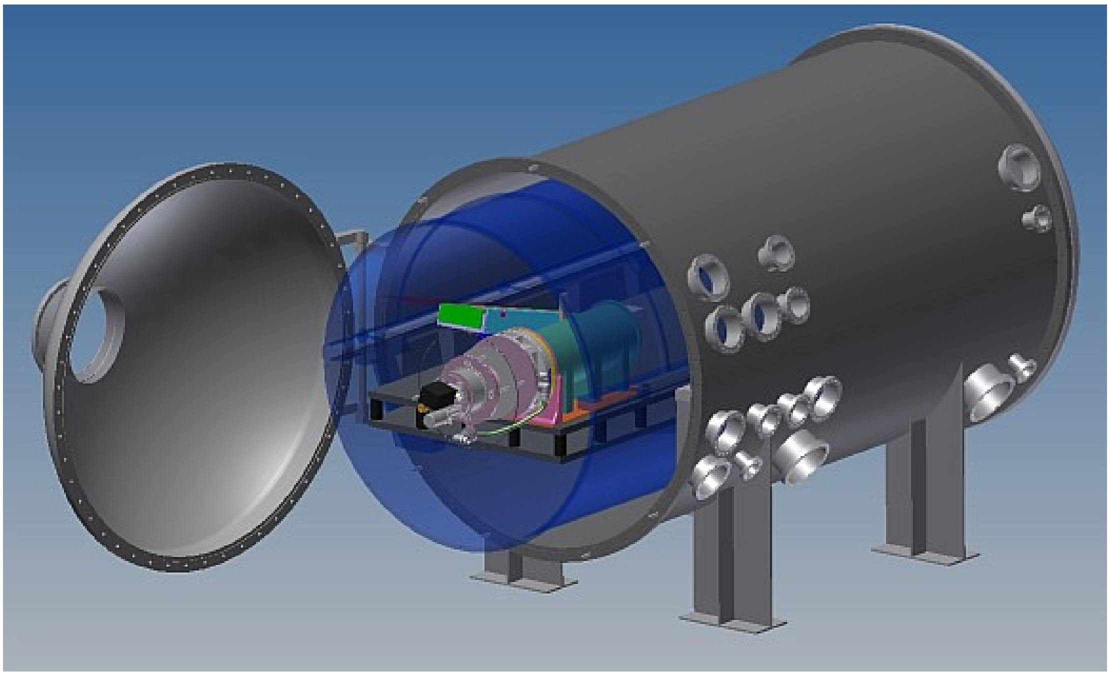

Figure 8.: Vacuum vessel with optical bench partially retracted and shield opened.

The opto-mechanical layout of an optical bench and optics mounts is shown in Fig. 9. All components are mounted on a flat light-weighted optical bench made of aluminum. The optical bench and all the main holders for the opto-mechanical components shall be treated in order to maximize stress relief. Artificial ageing is additionally provided by such technique. It means that the long-term deformation of the material is accelerated at the manufacturing stage so that it does not appear during the operational lifetime of CARMENES.

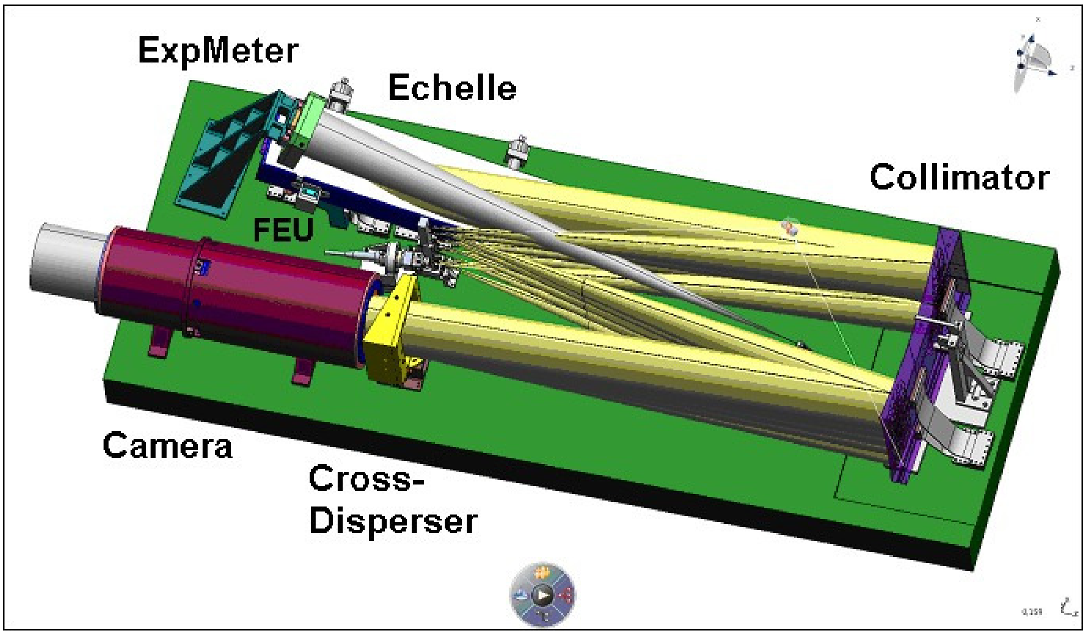

Figure 9.: Layout of the optical bench of the NIR channel.

The instrument consists in the following elements: the light enters through the fiber exit unit (FEU, grey, middle left) and then is sent via the collimator (violet, right side) to the échelle mosaic (blue, upper left). After passing collimator, folding mirror and transfer collimator again, it reaches the cross-disperser (yellow) and finally the camera (dark red, lower left). The envelope of the optical beam(s) is shown in yellow. Baffling and stops have been omitted in this figure for clarity. The detector cryostat is attached directly to the camera to facilitate the alignment and assembly between both subsystems.

The mirror above the échelle grating (light-green in the Fig. 9) and the corresponding beam envelope (grey) belong to the exposure meter. It picks up the zero order of the échelle grating and transfers/focuses it via a small off-axis mirror onto a large diameter fiber, located just in front of the unused part of the collimator mirror.

The fiber exit unit (Fig. 10) includes the support for the FN system as well as for the image slicer. It also includes the mechanical interface for the fiber feed.

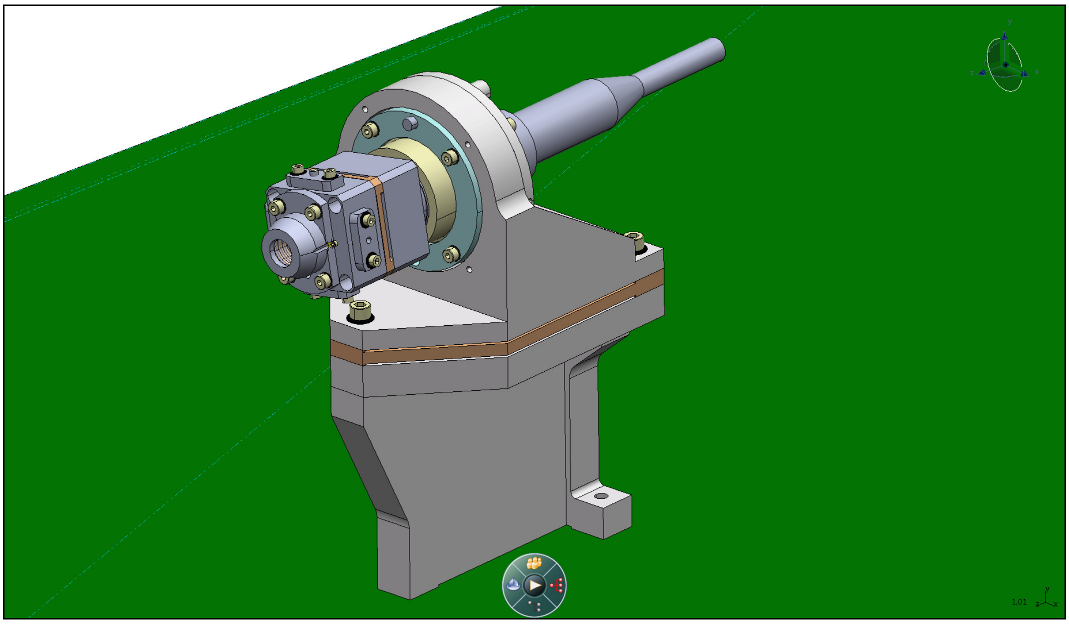

Figure 10.: Fiber exit unit.

The lenses of the camera barrel must be mounted in self-centering cells. These cells allow the lenses to remain centered with respect to the barrel even in the case of large thermal excursions. Each radial cell (see Fig. 11) is mounted inside its housing by means of a diametral fit. In its turn, each lens is mounted inside its radial cell by means of a diametral fit.

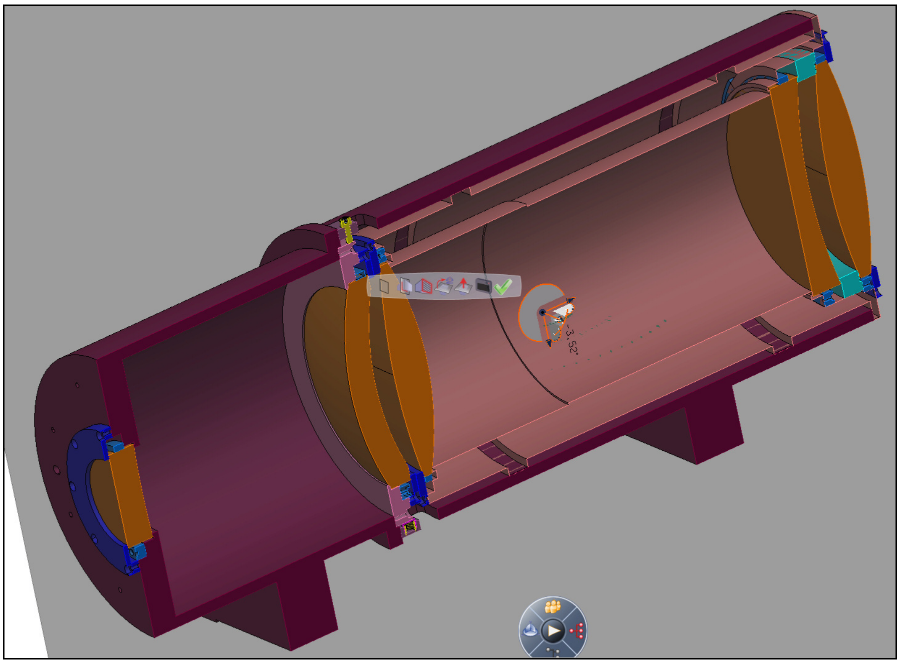

Figure 11. Camera barrel section.

Thermal couplings to the optical bench are necessary for the NIR channel to allow a fast heat transfer from the optical bench to every subsystem during cool-down process as well as temperature homogenization during operation. These thermal coupling are shown in the Fig. 12 for the échelle and in the Fig. 13 for the collimator mirror.

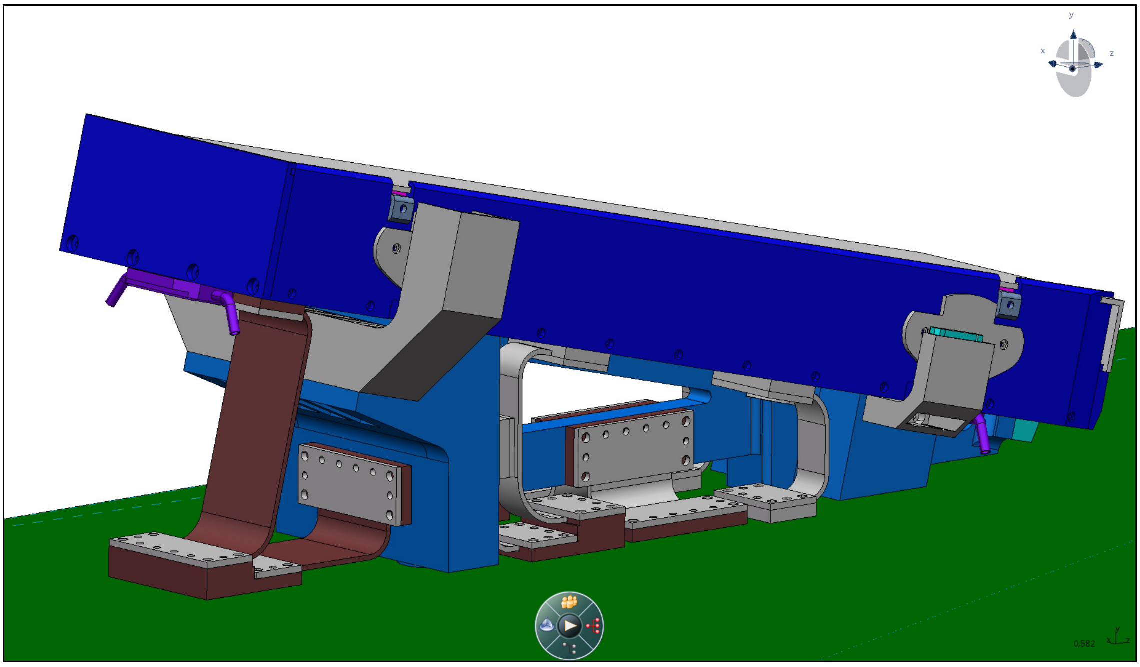

Figure 12.: Échelle support.

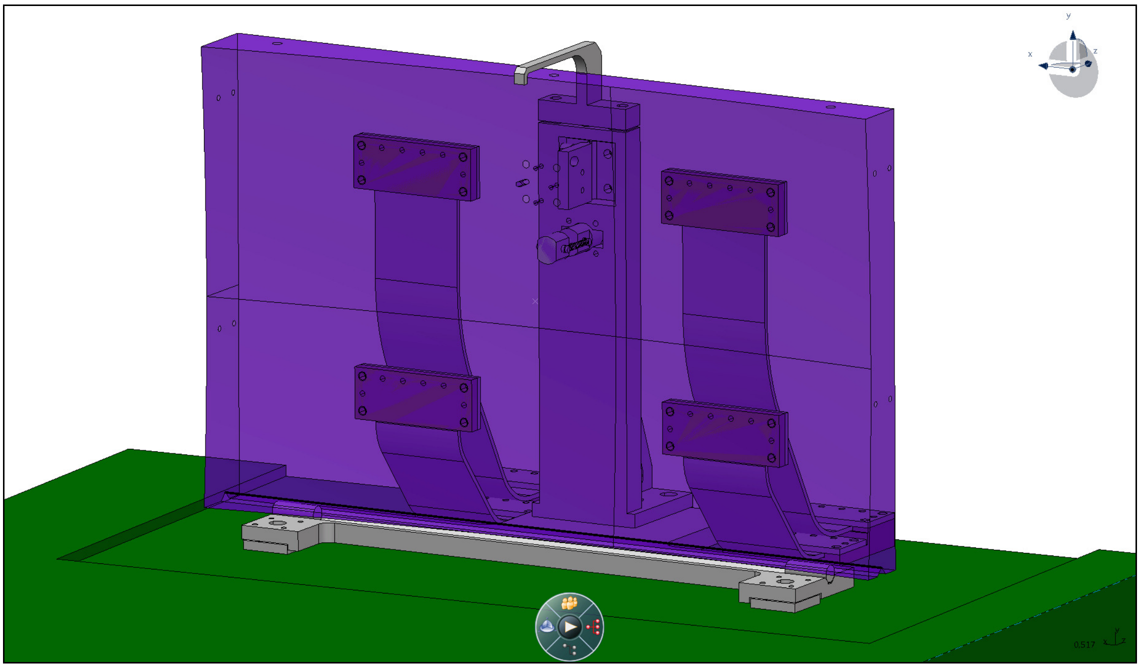

Figure 13.: Collimator mirror.

4. FRONT-END

The so-called front-end is the interface of the instrument to the telescope and provides the illumination of the fibers, both by star light and by calibration lights (see Fig. 14).

The pick-up mirror is moveable to allow sharing the Cassegrain focus between CARMENES and the integral field unit PMAS (Roth et al. 2005). A double atmospheric dispersion corrector is included in the beam, covering the full wavelength range from 550 to 1700 nm up to zenith distances of 70 deg. After the corrector, the light is splitted by a dichroic mirror into VIS and NIR to feed the corresponding fiber heads, each containing two fibers (object and calibration/sky). After the dichroic beam splitter, a second mirror is introduced to place the fiber heads for both channels close to each other in order to minimize differential flexure. Acquisition and guiding is done using the reflective surface of the VIS fiber head.

A large set of calibration lamps (UNe, ThArNe, etc.) are placed in the calibration units in the coudé room of the telescope. This ensures ease of maintenance and controlled conditions for the lamps. The calibration light is fed to the front-end via large diameter fibers and then projected onto the instrument fibers in the fiber heads. Parallel calibration via the second fiber is the standard mode for the instrument. For faint stars, the second fiber can be used for sky background determination; the calibrations have then to take place before and after the observations.

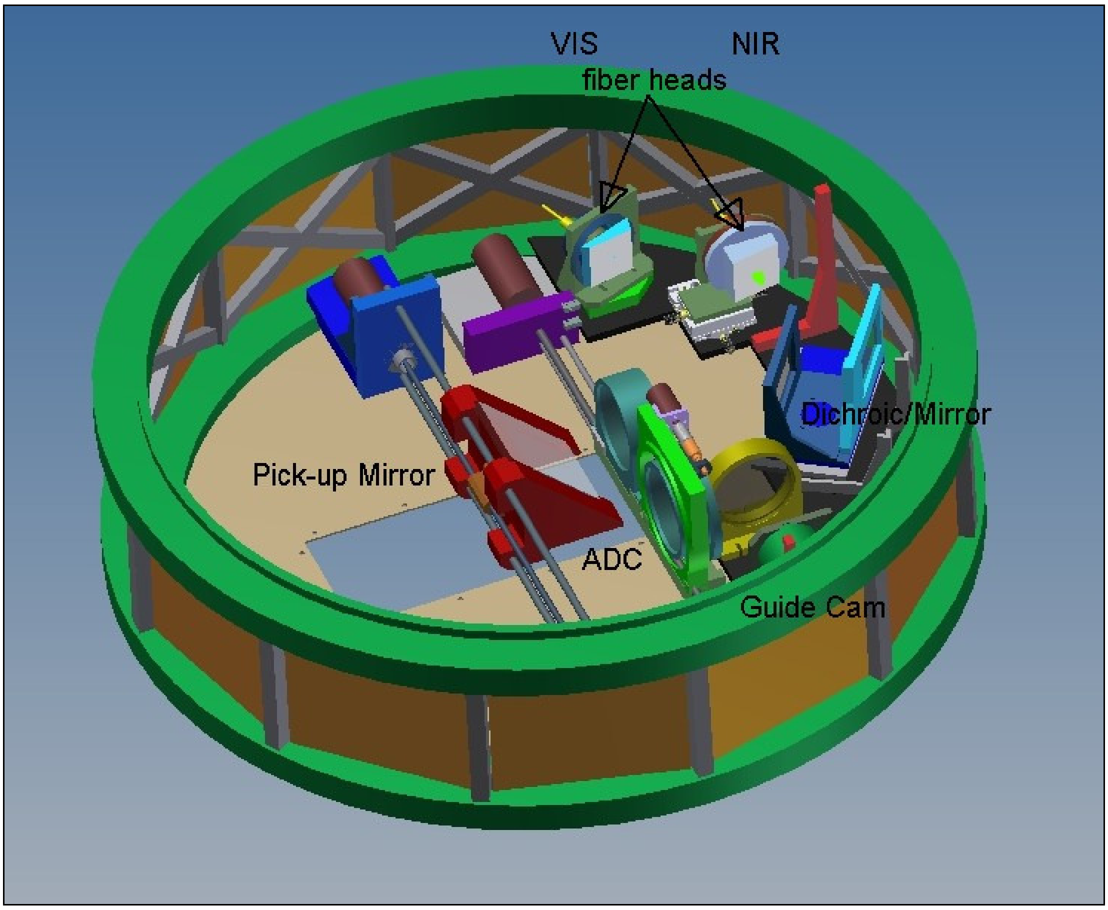

Figure 14.: 3D view of the front-end, i.e. the Cassegrain adapter. The rectangular hole in the baseplate will be cleared by the pick-up mirror when observations with PMAS are performed.

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REFERENCES

[1] Quirrenbach et al., ‘Calar Alto high-Resolution search for M dwarfs with Exo-earths with a Near-infrared Échelle Spectrograph’, SPIE, 7735, E37 (2010).
[2] Quirrenbach et al., ‘CARMENES. I: Instrument and survey overview’, SPIE, these proceedings (2012).
[3] Kaufer, A. et al., ‘FEROS, the fiber-fed extended range optical spectrograph for the ESO 1.52-m telescope’, Messenger, 89, 1 (1997)
[4] Kaufer, A., ‘A two-beam two-slice image slicer for fiber-linked spectrographs’, ASPC, 152, 337 (1998).
[5] Becerril, S. et al., ‘CARMENES. III: An innovative and challenging cooling system for an ultra-stable near-infrared spectrograph’, SPIE, these proceedings (2012).
[6] Roth et al., ‘PMAS: The Potsdam Multi-Aperture Spectrophotometer. I. Design, manufacture, and performance’, PASP, 117, 832 (2005).