

ESPRESSO: The next European exoplanet hunter

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The acronym ESPRESSO stems for Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations; this instrument will be the next VLT high resolution spectrograph. The spectrograph will be installed at the Combined-Coudé Laboratory of the VLT and linked to the four 8.2 m Unit Telescopes (UT) through four optical Coudé trains. ESPRESSO will combine efficiency and extreme spectroscopic precision. ESPRESSO is foreseen to achieve a gain of two magnitudes with respect to its predecessor HARPS, and to improve the instrumental radial-velocity precision to reach the 10 cm s^{-1} level. It can be operated either with a single UT or with up to four UTs, enabling an additional gain in the latter mode. The incoherent combination of four telescopes and the extreme precision requirements called for many innovative design solutions while ensuring the technical heritage of the successful HARPS experience. ESPRESSO will allow to explore new frontiers in most domains of astrophysics that require precision and sensitivity. The main scientific drivers are the search and characterization of rocky exoplanets in the habitable zone of quiet, nearby G to M-dwarfs and the analysis of the variability of fundamental physical constants. The project passed the final design review in May 2013 and entered the manufacturing phase. ESPRESSO will be installed at the Paranal Observatory in 2016 and its operation is planned to start by the end of the same year.

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1 Introduction

High-resolution spectroscopy provides physical insights in the study of stars, galaxies, and interstellar and intergalactic medium. Besides the importance of observing fainter and fainter objects by increasing the photon collecting area by making bigger telescopes, the importance of high-precision has emerged in recent years as a crucial element in spectroscopy. In many investigations repeatable observations over long temporal baseline are needed. For instance, the

HARPS spectrograph at the ESO 3.6-m telescope is a pioneering instrument for precise radial-velocity (RV) measurements (Mayor et al. 2003). The search for terrestrial planets in habitable zone is one of the most exciting science topics of the next decades and one of the main drivers for the new generation of Extremely Large Telescopes. The need for a similar instrument on the VLT has been emphasized in the ESO-ESA working group report on extrasolar planets. In October 2007 the ESO STC recommended the development of additional second-generation VLT instruments, and this proposal was endorsed by the ESO Council in December of the same year. Among the recommended instru-

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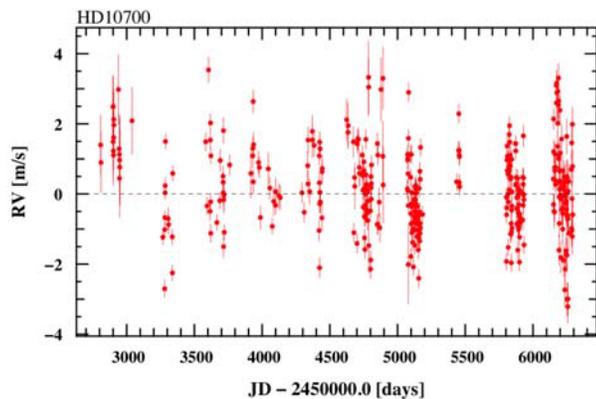


Fig. 1 Ten years of τ Ceti's RVs as measured by HARPS. The overall dispersion is of 1 m s^{-1} .

ments, a high-resolution, ultra-stable spectrograph for the VLT combined-Coudé focus arose as a cornerstone to complete the current 2nd generation VLT instrument suite. Following these recommendations, in March 2008 ESO issued a call for proposals to member state institutes or consortia to carry out the Phase-A study for such a instrument. The submitted proposal was accepted by ESO and the ESPRESSO Consortium¹ was selected to carry out the construction of this spectrograph in collaboration with ESO. The project kick-off was held in February 2011 and the design phase ended with the Final Design Review in May 2013. The procurement of components and manufacturing of subsystems will last about 18 months and early 2015 the subsystems will be ready for integration in Europe. Acceptance Europe of the instrument will be held in the fall 2015 while the transfer, installation and commissioning of the instrument at Paranal will take place in 2016. Acceptance Paranal is planned to take place at the end of 2016.

2 What science?

The main scientific drivers for the new spectrograph were defined by ESO as follows:

- measure high-precision RV for search for rocky planets;
- measure the variation of physical constants;
- analyse the chemical composition of stars in nearby galaxies.

2.1 Searching for rocky planets in the habitable zone

Terrestrial planets in the habitable zone of their parent stars are one of the main scientific topics of the next decades in

¹ The ESPRESSO Consortium is composed of: Observatoire Astronomique de l'Université de Genève (project head, Switzerland); Centro de Astrofísica da Universidade do Porto (Portugal), Faculdade de Ciências da Universidade de Lisboa (Portugal); INAF-Osservatorio Astronomico di Brera (Italy); INAF-Osservatorio Astronomico di Trieste (Italy); Instituto de Astrofísica de Canarias (Spain); Physikalisches Institut der Universität Bern (Switzerland); ESO participates to the ESPRESSO project as Associated Partner and contributes the Echelle grating, the camera lenses, the detector system and the cryogenic and vacuum control system.

Astronomy, and one of the main science drivers for the new generation of extremely large telescopes. ESPRESSO, being capable of achieving a precision of 10 cm s^{-1} in terms of RV, will be able to register the signals of Earth-like planets in the habitable zones (i.e., in orbits where water is retained in liquid form on the planet surface) around nearby solar-type stars and around stars smaller than the Sun. Since 1995 research teams using the RV technique have discovered about 600 extrasolar planets, some of which with only a few times the mass of the Earth. Today, dozens of detected RV extrasolar planets have estimated masses below 10 Earth masses, and most of them were identified using the HARPS spectrograph (e.g. Mayor et al. 2011). The rate of these discoveries increases steadily. The HARPS high-precision RV program has shown that half of the solar-like stars in the sky harbour Neptune-mass planets and super-Earths, a finding also supported by the recent discoveries of the *Kepler* satellite (e.g. Howard et al. 2012). These exciting discoveries were made possible thanks to the sub- m s^{-1} precision reached by HARPS. In Fig. 1 are shown 10 years of RVs measured by HARPS for Tau Ceti. The overall dispersion is of 1 m s^{-1} , but time-binning of the data will reduce the dispersion down to 20 cm s^{-1} with the absence of any long-term trend. Most of the discovered exoplanets would have remained out of reach if existing facilities had been limited to 3 m s^{-1} .

Considering the observational bias towards large masses, one should expect a huge amount of still undiscovered low-mass planets, even in already observed stellar samples. The most recent planet formation theories support this view and the detected population is probably only the tip of the iceberg, and the bulk is still to be discovered. ESPRESSO is designed to explore this new mass domain and charter unknown territories. This goal can only be obtained by combining high efficiency with high instrumental precision. ESPRESSO will be optimized to obtain best RVs on quiet solar-type stars. A careful selection of these stars will allow to focus the observations on the best-suited candidates: non-active, non-rotating, quiet G to M dwarfs. An optimized observational strategy will permit the characterization of the planetary systems and very low-mass planets despite stellar noise. An impressive demonstration that this approach is realistic has been recently delivered by detecting a 1 Earth-mass planet around our neighbour α Cen B (Dumusque et al. 2012).

With a precision of 10 cm s^{-1} (about a factor of 10 better than HARPS), it will be possible to detect rocky planets down to the Earth mass in the habitable zone of solar-type stars. For comparison, the Earth imposes a velocity amplitude of 9 cm s^{-1} onto the Sun. As shown in Fig. 2 by extending the sample towards the lighter M-stars, the task becomes even easier since the RV signal increases with decreasing stellar mass. ESPRESSO will operate at the peak of its efficiency for a spectral type up to M4-type stars. The discovery and the characterization of a new population of very light planets will open the door to a better understanding of

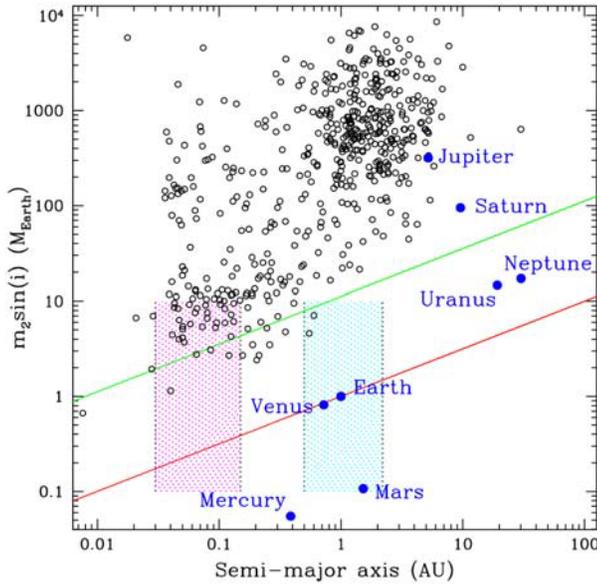


Fig. 2 Detectability of planets orbiting a $0.8 M_{\odot}$ star (red solid line) and a $1 M_{\odot}$ star (green solid line) in the mass vs. semi-major axis plane expected for ESPRESSO. The detectability curves have been calculated assuming a velocity amplitude of 10 cm s^{-1} (for the $0.8 M_{\odot}$ star) and 1 m s^{-1} (for the $1 M_{\odot}$ star), null eccentricity, and $\sin i = 1$. Known RV planets of solar-type stars are plotted as open circles, and the planets of the solar system (solid circles) are labeled. The “habitable zones” of $0.8\text{--}1.2 M_{\odot}$ and $0.2\text{--}0.3 M_{\odot}$ stars are indicated with blue and pink dotted lines, respectively. These are regions where rocky planets with a mass in the interval $0.1\text{--}10$ of the mass of the Earth can retain liquid water on their surface.

planet formation and deliver new candidates for follow-up studies by using other techniques such as transit, astrometry, Rossiter-McLaughlin effect, etc. Another important task for ESPRESSO will be the follow-up of transiting planets. It should be recalled that many *Kepler* transit candidates are too faint to be confirmed by existing RV instruments. Other satellites like GAIA, TESS and hopefully PLATO will provide us with many new transit candidates, possibly hosted by bright stars. ESPRESSO will be the ideal (and maybe unique) machine to make spectroscopic follow-up of Earth-size planets discovered by the transit technique. Besides, being an exquisite RV machine, ESPRESSO will provide extra-ordinary and stable spectroscopic observations, opening new possibilities for transit spectroscopy and analysis of the light reflected by the exoplanet. Several groups are currently investigating to which extent this will be feasible in the visible and infrared spectral domain (see, e.g., Snellen 2013; Snellen et al. 2013, and references therein). Fast-cadence spectra of the most promising candidates will provide estimates of the maximum frequency of solar-like oscillations. The resulting seismic constraints on the gravity of the host stars and precise spectroscopic analysis will allow us to improve the determination of the mass and radius of the star and, therefore, of the planet (Chaplin & Miglio 2013). ESPRESSO should be considered an important de-

velopment step towards obtaining high-precision spectrographs on the ELT.

2.2 Do physical constants vary?

The standard model of particle physics depends on many (≈ 27) independent numerical parameters that determine the strengths of the different forces and the relative masses of all known fundamental particles. There is no theoretical explanation for their actual value, but nevertheless they determine the properties of atoms, cells, stars and the whole Universe. They are commonly referred to as the fundamental constants of nature, although most of the modern extensions of the standard model predict a variation of these constants at some level (see Uzan 2011; Bonifacio et al. 2013). For instance, in any theory involving more than four space-time dimensions, the constants we observe are merely four-dimensional shadows of the truly fundamental high dimensional constants. The four dimensional constants will then be seen to vary as the extra dimensions change slowly in size during their cosmological evolution. An attractive implication of quintessence models for the dark energy is that the rolling scalar field produces a negative pressure and therefore the acceleration of the universe may couple with other fields and be revealed by a change in the fundamental constants (Amendola et al. 2013). Earth-based laboratories have so far revealed no variation in their values. For example, the constancy of the fine structure constant α is ensured to within a few parts per 10^{-17} over a 1-yr period (Rosenband et al. 2008). Hence their status as truly *constants* is amply justified.

Astronomy has a great potential in probing their variability at very large distances and in the early Universe. In fact, the transition frequencies of the narrow metal absorption lines observed in the spectra of distant quasars are sensitive to α (e.g. Bahcall et al. 1967) and those of the rare molecular hydrogen clouds are sensitive to μ , the proton-to-electron mass ratio (e.g. Thompson 1975). With the advent of 10-m class telescopes, observations of spectral lines in distant QSOs gave the first hints that the value of the fine structure constant might change over time, being lower in the past by about 6 ppm (Webb et al. 1999; Murphy et al. 2004). The addition of other 143 VLT/UVES absorbers (Fig. 3) have revealed a 4σ evidence for a dipole-like variation in α across the sky at the 10 ppm level (Webb et al. 2011; King 2012). Several other constraints from higher-quality spectra of individual absorbers exist but none of them directly supports or strongly conflicts with the α dipole evidence, and a possible systematic producing opposite values in the two hemispheres is not easy to identify.

In order to probe μ , the H_2 absorbers need to be at a redshift $z > 2\text{--}2.5$ to place the Lyman and Werner H_2 transitions redwards of the atmospheric cut-off. Only five systems have been studied so far, with no current indication of variability at the level of 10 ppm (e.g. Rahmani et al. 2013). At lower redshifts precise constraints on μ -variation are available from radio- and millimeter-wave spectra of

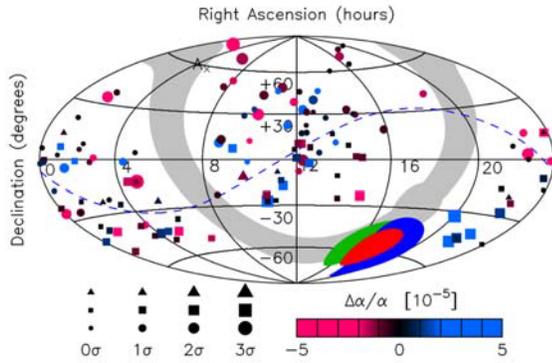


Fig. 3 All-sky spatial dipole with the combined VLT (squares) and Keck (circles) α measurements from Webb et al. (2011). Triangles are measures in common with the two telescopes. The blue dashed line shows the equatorial region of the dipole.

cool clouds containing complex molecules like ammonia and methanol (see, e.g., Flambaum & Kozlov 2007; Levskakov et al. 2013). Other techniques involving radio spectra typically constrain combinations of constants by comparing different types of transitions (e.g. electronic, hyperfine, rotational, etc.).

Extraordinary claims require extraordinary evidence, and a confirmation of variability with high statistical significance is of crucial importance. Only a high resolution spectrograph that combines a large collecting area with extreme wavelength precision can provide definitive clarification. A relative variation in α or μ of 1 ppm leads to velocity shifts of about 20 m s^{-1} between typical combinations of transitions. ESPRESSO is expected to provide an increase in the accuracy of the measurement of these two constants by at least one order of magnitude compared to VLT/UVES or Keck/HIRES. More stringent bounds are also important and the ones already provided constrain the parameter space of various theoretical models that predict their variability.

2.2.1 Chemical composition of stars in local galaxies

One important piece of information in the understanding of the galaxy formation is the chemical composition of local galaxies. In spite of the many successes in this field, the majority of local galaxies still lack detailed abundance information. For about a dozen of nearby galaxies observable from Paranal chemical information is available, albeit, except Sagittarius, for a few stars and for a limited set of elements, and for the faintest galaxies it is based on low to medium resolution spectra. The next nearest galaxy, Leo T, has a distance modulus of 23.1, i.e. more than one magnitude more distant than Leo I ($m - M = 21.99$). The local group galaxies all possess giant stars of magnitude $V = 20$ or fainter. Although some work has been done with UVES at VLT at this magnitude, it is really difficult to obtain accurate chemical abundances. For galaxies that possess a young population, like Phoenix or WLM, one can rely on bright O and B supergiants. However, if one considers old metal-

poor systems, like Boötes or Hercules, one has to rely on red giants. Although it is clear that most of the chemical information for local galaxies will have to come largely from the ELT, ESPRESSO will give us the chance to have a first but important glimpse into this.

2.3 A scientific Pandora box

ESPRESSO combines an unprecedented RV and spectroscopic precision with the largest photon collecting area available today at ESO and unique resolving power ($R \sim 200\,000$). It will certainly provide breakthroughs in many areas of astronomical research, many of which cannot be anticipated. We shall provide just few examples below.

- *The expanding Universe.* Sandage (1962) first argued that in any cosmological model the redshifts of cosmologically distant objects drift slowly with time. If observed, their redshift drift-rate, dz/dt , would constitute evidence of the Hubble flow's deceleration or acceleration between redshift z and today. Indeed, this observation would offer a direct, non-geometric, completely model-independent measurement of the Universe's expansion history (Liske et al. 2008). ESPRESSO, even in the 4UT mode, is probably not sufficiently sensitive to measure the tiny signal which is at the level of few $\text{cm s}^{-1} \text{ yr}^{-1}$. However, it might provide first accurate historical reference measurements and in any case will represent an important step forward in setting the scene for the next generation of high resolution spectrographs at the E-ELTs.
- *Metal poor stars.* The most metal poor stars in the Galaxy are probably the most ancient fossil records of the chemical composition and thus can provide clues on the pre-Galactic phases and on the stars which synthesized the first metals. Masses and yields of Pop. III stars can be inferred from the observed elemental ratios in the most metal poor stars (Heger & Woosley 2010). One crucial question to be answered is the presence of Pop. III low-mass stars. For a long time the Pop. III stars have been thought to be only very massive but the recent discovery of a very metal-poor star with $[\text{Fe}/\text{H}] \sim -5.0$ and *normal* C and N have shown an entirely new picture (Caffau et al. 2011). Several surveys searching for metal poor stars are currently going on or are planned, and thousands of EMP stars with $[\text{Fe}/\text{H}] < -3.0$, of which maybe several down to $[\text{Fe}/\text{H}] \approx -5.0$ and hopefully lower, are expected to be found. These will be within the reach of ESPRESSO, which will be able to provide spectra for an exquisite chemical analysis in both the 1-UT and 4-UT modes.
- *Stellar oscillations, asteroseismology, variability.* Stars located in the upper main sequence show non-radial pulsations that cause strong line profile variations. Asteroseismic study (i.e., mode identification) of these pulsating stars (γ Dor, δ Sct, β Cep, SPB, etc.) provides constraints on the structure of massive stars (e.g. internal

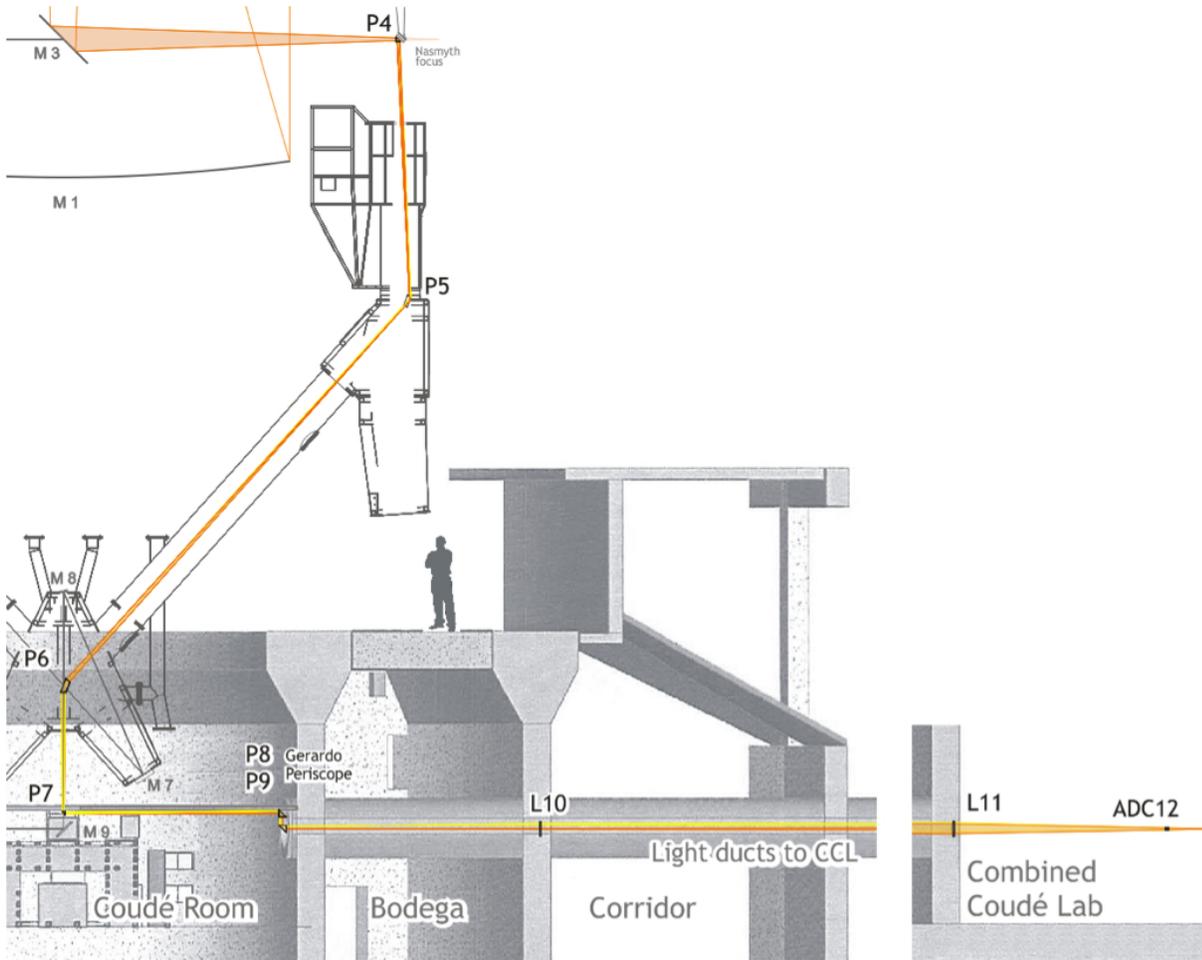


Fig. 4 Coudé train of ESPRESSO and optical path through the telescope and the tunnels.

convection, overshooting, core size, extension of acoustic and gravity cavities, mass loss phenomena, interplay between rotation and pulsation). ESPRESSO will allow us to perform the short exposures required to identify the high-frequency modes, currently achievable on a wide variety of stars only with photometry from space.

- *Galactic winds and tomography of the IGM.* In principle, spectroscopy of close, multiple, high-redshift quasars allows to recover the 3-dimensional distribution of matter from the analysis of the H I Ly α absorption lines. If the multiple lines of sight cross a region where high-redshift galaxies are present, it is also possible to investigate the properties of outflows and inflows, studying the spectral absorption lines at the redshift of the galaxies and how they evolve moving closer to or far away from the galaxies themselves. The main limitation to the full exploitation of the so-called *tomography* of the IGM is the dearth of quasar pairs at the desired separation, bright enough to be observed with the present high-resolution spectrographs at 10 m-class telescopes. ESPRESSO used in the 4UT mode would result in a gain of ≈ 1.5 magnitude fainter than, e.g., UVES, translating into an almost a 20-fold increase in the number

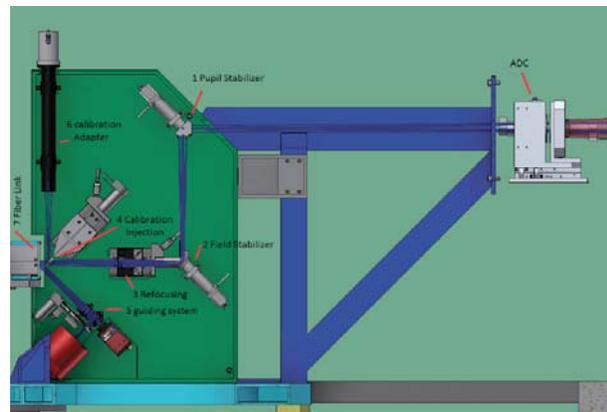


Fig. 5 Side view of the Front-End and the arrival of one UT beam at the CCL. The same is replicated for the other UTs.

of observable quasar pairs with separation lower than 3 arcmin and emission redshift in the range $2 < z < 3$.

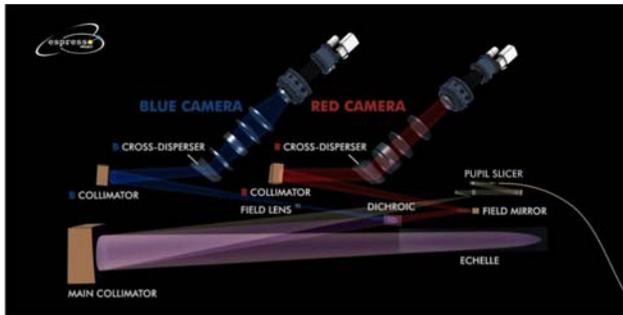


Fig. 6 Layout of the ESPRESSO spectrograph and its optical elements.

3 A new-generation instrument for the VLT

ESPRESSO is a fibre-fed, cross-dispersed, high-resolution échelle spectrograph which will be located in the Combined Coudé Laboratory (CCL) at the incoherent focus, where a front-end unit can combine the light from up to 4 Unit Telescopes (UT) of the VLT. The telescope light is fed to the instrument via a so-called Coudé-train optical system. The target and sky light enter the instrument simultaneously through two separate fibres, which together form the *slit* of the spectrograph. Although foreseen since 1977 in the original VLT plan, the incoherent combined focus of the VLT has never been implemented. Only provision for it, in terms of space left in the UTs structures and ducts in the rock of the mountain, is what is actually available at the VLT. As part of the project agreement, the ESPRESSO Consortium has been asked to materialize such a focus providing the necessary hardware and software as part of the deliverables. The implementation of the Coudé train leads to substantial changes in the Paranal Observatory infrastructure and requires an elaborate interfaces management. ESPRESSO will be located in the VLT's CCL and, unlike any other instrument built so far, will receive light from any of the four UTs. The light of the single UT scheduled to work with ESPRESSO is then fed into the spectrograph (1-UT mode). Alternatively, the combined light of all the UTs can be fed into ESPRESSO simultaneously (4-UT mode).

3.1 The Coudé train

Distances between the UTs and the CCL range between 48m for UT2 to 69 m for UT1. A trade-off analysis between solutions based on mirrors, prisms, lenses and fibres pointed towards a full optics solution, i.e. using only conventional optics without fibres for transporting the light from the telescope into the CCL. The chosen design with the position of the 11 optical elements is shown in Fig 4. The Coudé train picks up the light with a prism at the level of the Nasmyth-B platform and routes the beam through the UT mechanical structure down to the UT Coudé room, and farther to the CCL along the existing incoherent light ducts. The four trains relay a field of 17 arcsec around the acquired object to the CCL. The selected concept to convey the light of the

telescope from the Nasmyth focus (B) to the entrance of the tunnel in the Coudé room (CR) below each UT unit is based on a set of 6 prisms (with some power). The light is directed from the UT's Coudé room towards the CCL using 2 large lenses. The beams from the four UTs meet in the CCL, where mode selection and beam conditioning is performed by the fore-optics of the Front-End subsystem.

3.2 The Front-End

The Front-End transports the beam received from the Coudé, once corrected for atmospheric dispersion by the ADC, to the common focal plane where the pickups for the spectrograph fiber feeds are located. While performing such a beam conditioning the Front-End applies pupil and field stabilization. They are achieved via two independent control loops each composed of a technical camera and a tip-tilt stage. Another dedicated stage delivers a focusing function. In addition, the Front-End handles the injection of the calibration light, prepared in the Calibration Unit, into the fibers and then into the spectrograph. As calibration sources we foresee a laser frequency comb (LFC), with as backup two ThAr lamps (one for simultaneous reference and one for calibration) and a calibration light is foreseen to be composed of 2 ThAr, one for simultaneous Fabry-Pérot unit. A top view of the Front-End arrangement is shown in Fig. 5. A toggling mechanism shown in Fig. 8 handles the selection between the possible observational modes described below in a fully passive way.

The Fibre-Link subsystem relays the light from the Front-End to the spectrograph and forms the spectrograph pseudo-slit inside the vacuum vessel. The 1-UT mode uses a bundle of 2 octagonal fibres each, one for the object and one for the sky or simultaneous reference. In the high-resolution (singleHR) mode the fiber has a core of 140 μm , equivalent to 1 arcsec on the sky; in the ultra-high resolution (singleUHR) mode the fibre core is 70 μm and the covered field of view 0.5 arcsec. The fibre entrances are organized in pickup heads that are moved to the focal plane of the Front End when the specific bundle of the specific mode is selected. In the 4-UT mode (multiMR) four object fibres and four sky/reference fibres are fed simultaneously by the four telescopes. The four object fibres will finally feed a single square 280 μm object fibre, while the four sky/reference fibres will feed a single square 280 μm sky/reference fibre. Also in the 4-UT mode the spectrograph will see a pseudo slit of four fibre images, although they will be square and twice as wide as the 1-UT fibres. Another essential task performed by the Fibre-link subsystem is the light scrambling. The use of a double-scrambling optical system will ensure both scrambling of the near field and far field of the light beam. A high scrambling gain, which is crucial to obtain the required RV precision in the 1-UT mode is achieved by the use of octagonal fibres (Chazelas et al. 2011).

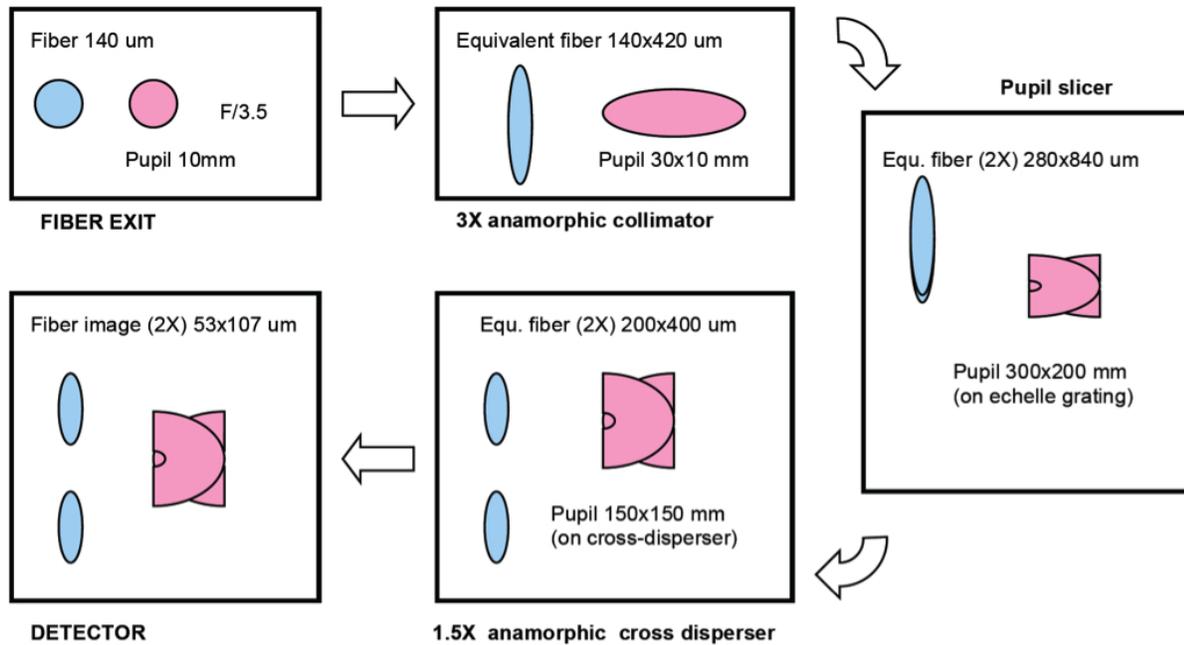


Fig. 7 Conceptual description of pupil and fibre image at relevant locations of the spectrograph optical path.

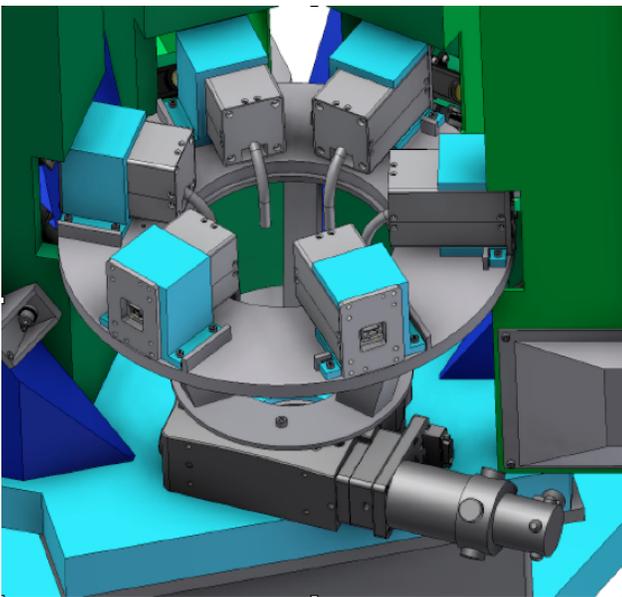


Fig. 8 Toggling mechanism for the selection of the observing mode.

3.3 Observing modes

The extreme precision of ESPRESSO will be obtained by improving well-known HARPS concepts. The light of one or several UTs is fed by means of the front-end unit into optical fibres that scramble the light and provide excellent illumination stability to the spectrograph. In order to improve light scrambling, non-circular fibre shapes will be used. The target fibre can be fed either with the light from the astronomical object or one of the calibration sources. The reference fibre will receive either sky light (faint source mode)

or calibration light (bright source mode). In the latter case – the famous simultaneous-reference technique adopted in HARPS – it will be possible to track instrumental drifts down to the cm s^{-1} level. In this mode the measurement is photon-noise limited and detector read-out noise negligible. In the faint-source mode, instead, detector noise and sky background may become significant. In this case, the second fibre will allow to measure the sky background, while a slower read-out and high binning factor will reduce the detector noise. As summarized in Table 1, ESPRESSO will have three instrumental modes: singleHR, singleUHR and multiMR. Each mode will be available with two different detector read-out modes optimized for low and high-SNR measurements, respectively. In high-SNR (high-precision) measurements the second fibre will be fed with the simultaneous reference, while in the case of faint objects it shall be preferred to feed the second fibre with sky light. A schematic view of the different observing modes is shown in Fig. 9.

3.4 Performances

The observational efficiency of ESPRESSO is shown in Figs. 10 and 11. In the singleHR, $R \approx 134\,000$ mode, a $\text{SNR} = 10$ per extracted pixel is obtained in 20 minutes on a $V = 16.3$ star, or a $\text{SNR} = 540$ on a $V = 8.6$ star. We have estimated that at this resolution this SNR value will lead to 10 cm s^{-1} RV precision for a non-rotating K5 star. For an F8 star, the same precision would be achieved for $V = 8$. In the multiMR mode, at $R \approx 60\,000$, a $\text{SNR} \approx 10$ is achieved on a $V = 19.4$ star with a 20 minute exposure, a binning 2×4 , and a slow read-out of the CCD.

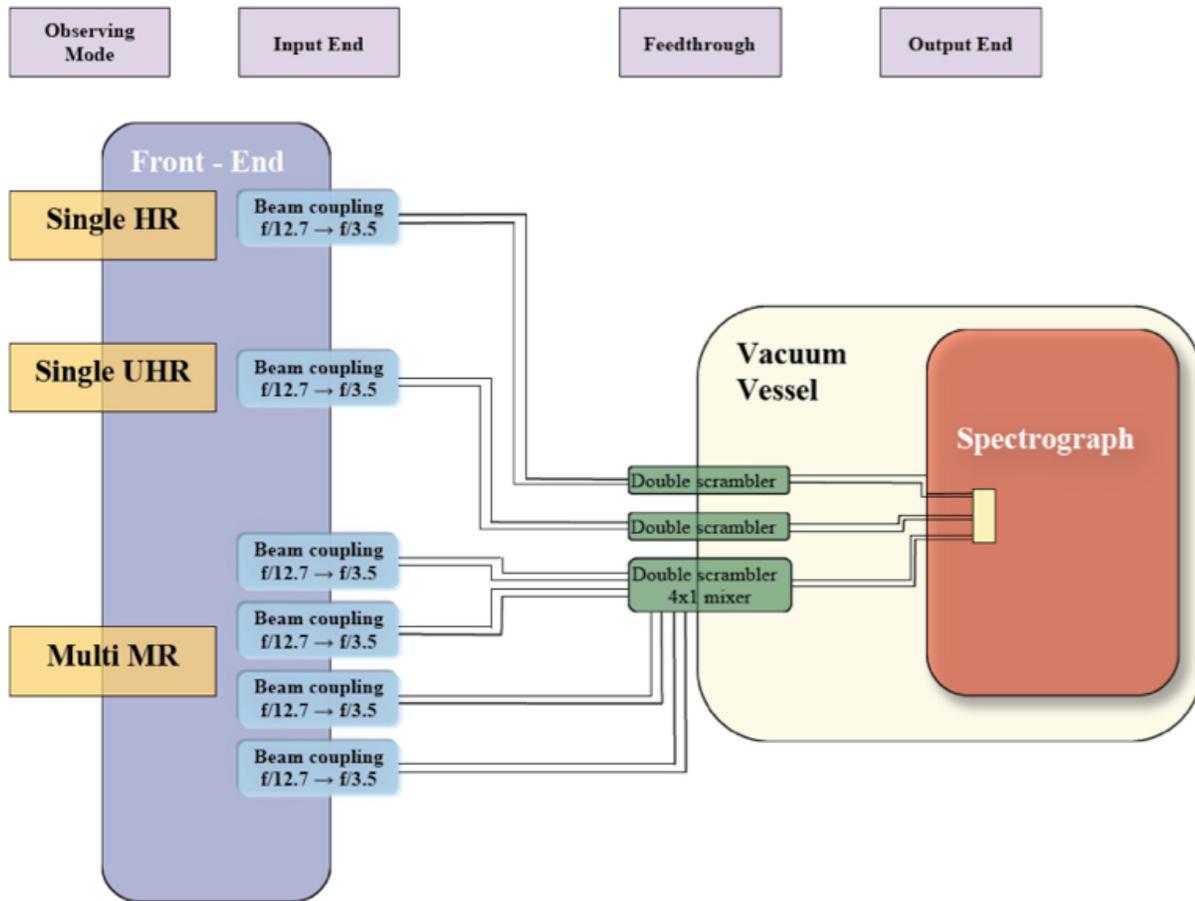


Fig. 9 Scheme of the different observing modes.

Table 1 ESPRESSO's observing modes.

Par./Mode	HR (1UT)	MR(4UTs)	UHR
Wave. range	380–780 nm	380–780 nm	380–780 nm
Resol. Power	134 000	59 000	≈ 200 000
Aper. on Sky	1'0	4'' × 1''	0'5
Spec. Samp.	4.5 pix	11 pix	2.5 pix
Spat. Samp.	11 × 2 pix	22 × 2 pix	5 × 2 pix
Sim. Ref.	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky Sub.	Yes (no ref.)	Yes (no ref.)	Yes (no ref.)
Tot. Eff.	11 %	11 %	5 %

3.5 Design

Several *tricks* have been used to obtain high spectral resolution and efficiency despite the large size of the telescope and the 1 arcsec sky aperture of the instrument. In order to minimize the size of the optics, particularly of collimator and échelle grating, ESPRESSO implements an anamorphic optics, the APSU, which compresses the size of the pupil in the direction of the cross-dispersion. The pupil is then sliced in two by a pupil slicer and the slices are overlapped on the échelle grating, leading to a doubled spectrum on the detector. The shape and size of both the pupil and the fibre image is shown in Fig. 7 for various locations along the op-

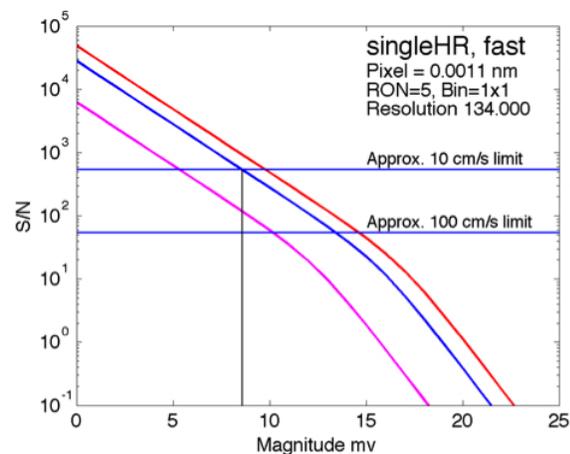


Fig. 10 Achievable signal-to-noise ratio as a function of stellar visible magnitude for the singleHR. Red, blue, and violet curves indicate exposure times of 3600 s, 1200 s, and 60 s, respectively.

tical beam of the spectrograph. Without using this method, the collimator beam size would have been 40 cm in diameter and the size of the échelle grating would have reached a size of 240 × 40 cm. The actual ESPRESSO design foresees the use of an Echelle grating of *only* 120 × 20 cm and

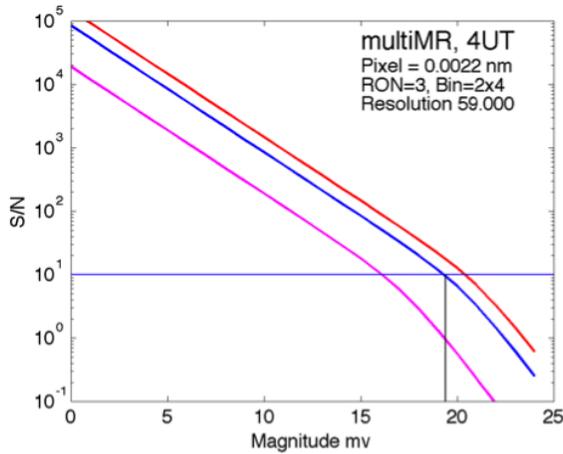


Fig. 11 As Fig. 10 but for the multiMR mode with binning of 2×4 pixels.

of much smaller optics (collimators, cross dispersers, etc.). The échelle grating will be an R4 Echelle of 31.6 l mm^{-1} and a blaze angle of 76° . This solution significantly reduces the overall costs. The drawback is that each spectral element will be covered by more detector pixels given the doubled image of the target fibre and its elongated shape on the CCD. In order to avoid increased detector noise, heavy binning will be done in the case of faint-object observations, especially in the 4-UT mode.

- *The Anamorphic Pupil Slicing Unit (APSU)*. At the spectrograph entrance the APSU shapes the beam in order to compress it in cross-dispersion and splits in two smaller beams, while superimposing them on the Echelle grating to minimize its size. The rectangular white pupil is then re-imaged and compressed.
- *Dichroic*. Given the wide spectral range, a dichroic beam splitter separates the beam in a blue and a red arm, which in turn allows to optimizing each arm for image quality and optical efficiency.
- *Volume Phase Holographic Gratings (VPHGs)*. The cross-disperser has the function of separating the dispersed spectrum in all its spectral orders. In addition, an anamorphism is re-introduced to make the pupil square and to compress the order height such that the inter-order space and the SNR per pixel are both maximized. Both functions are accomplished using Volume Phase Holographic Gratings (VPHGs) mounted on prisms.
- *Fast Cameras*. Two optimised camera lens systems image the full spectrum from 380 nm to 780 nm on two large 92×92 mm CCDs with $10\text{-}\mu\text{m}$ pixels. The blue camera is shown in Fig. 13 has an entrance aperture of 150×150 mm, a Focal length of 400 mm at 450 nm and a focal ratio of $F/2.6$.

A sketch of the optical layout is shown in Fig. 6. The spectral format covered by the blue and the red chips as well as the shape of the pseudo slit are shown in Fig. 12. The spectrograph is also equipped with an advanced exposure

meter that measures the flux entering the spectrograph as a function of time. This function is necessary to compute the weighted mean time of exposure at which the precise relative Earth motion must be computed and corrected for in the RV measurement. Its innovative design (based on a simple diffraction grating) allows a flux measurement and an RV correction at different spectral channels, in order to cope with possible chromatic effects that could occur during the scientific exposures. The use of various channels also provides a redundant and thus more reliable evaluation of the mean time of exposure.

3.6 The opto-mechanics

ESPRESSO is designed to be an ultra-stable spectrograph capable of reaching RV precisions of the order of 10 cm s^{-1} , i.e. one order of magnitude better than its predecessor HARPS. ESPRESSO is therefore designed with a totally fixed configuration and for the highest thermo-mechanical stability. The spectrograph optics are mounted in a 3-dimensional optical bench specifically designed to keep the optical system within the thermo-mechanical tolerances required for high-precision RV measurements. The bench is mounted in a vacuum vessel in which 10^{-5} mbar class vacuum is maintained during the entire duty cycle of the instrument. An overview of the opto-mechanics is shown in Fig. 14. The temperature at the level of the optical system is required to be stable at the mK level in order to avoid both short-term drift and long-term mechanical instabilities. Such an ambitious requirement is obtained by locating the spectrograph in a multi-shell active thermal enclosure system as shown in Fig. 15. Each shell will improve the temperature stability by a factor 10, thus getting from typically Kelvin-level variations in the CCL down to 0.001 K stability inside the vacuum vessel and on the optical bench.

3.7 Large-area CCDs

ESPRESSO presents also innovative solutions in the area of the CCDs, their packages and cryostats. One of the world's largest monolithic state-of-the-art CCDs was selected to properly utilize the optical field of ESPRESSO and to further improve the stability compared to a mosaic solution, as employed in HARPS. The sensitive area of the e2v chip is 92×92 mm covering 8.46×10^7 pixels of $10 \mu\text{m}$ size. Fast read out of such a large chip is achieved by using its 16 output ports at high speed. Other requirements on CCDs are very demanding, e.g. in terms of Charge Transfer Efficiency (CTE) and all the other parameters affecting the definition of the pixel position, immediately reflected into the radial-velocity precision and accuracy. The CCDs are currently being procured by ESO from the e2v supplier. First engineering devices have already been received and one is shown in Fig. 16. First warm technical light with the ESO custom-made components (NGC controller, cabling, cryostat electronics, firmware and mock-up mechan-

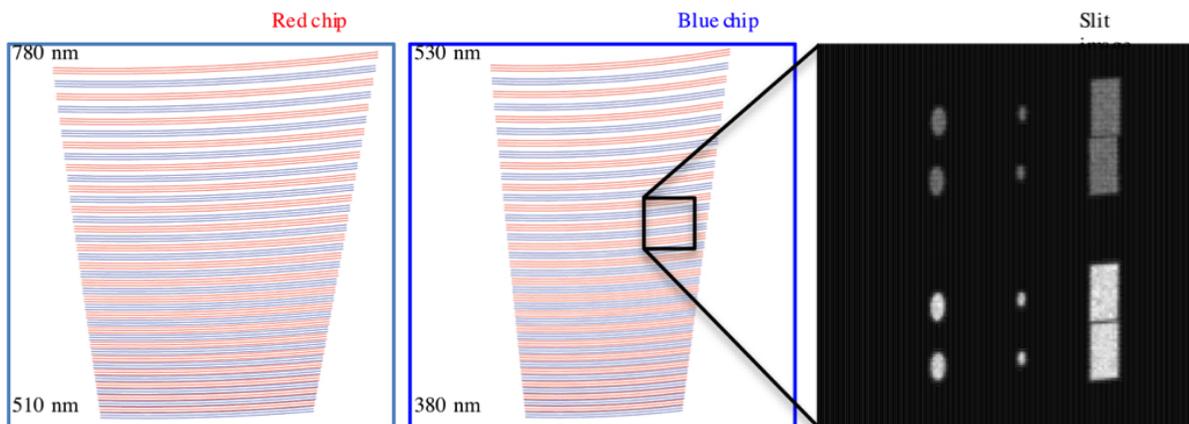


Fig. 12 *Left*: format of the red spectrum; *middle*: format of the blue spectrum; *right*: zoom on the pseudo slit. This latter shows the image of the target (bottom) and sky fiber (top). Each fiber is re-imaged in two slices. The three sets of fibers corresponding (from left to right) to the standard resolution 1-UT mode, ultra-high resolution 1-UT mode, and mid-resolution 4-UT mode, are shown simultaneously.

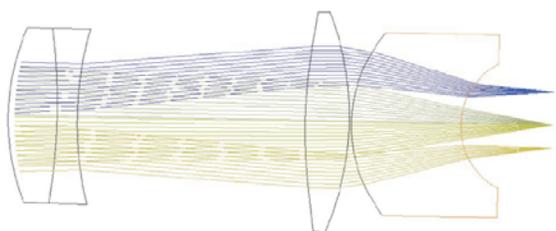


Fig. 13 Blue Camera elements. More than 80 % of encircled energy measured at 9 wavelengths for all orders results within the CCD pixel size of $10 \mu\text{m}$.

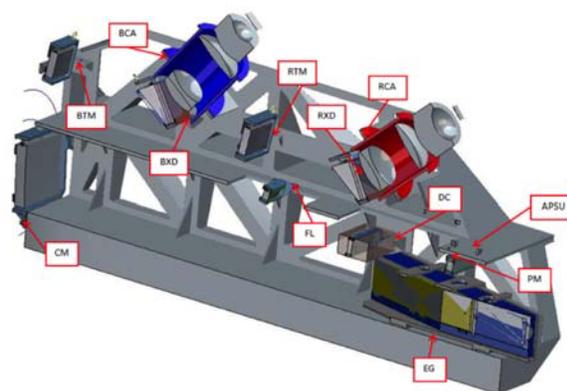


Fig. 14 Opto-mechanics of the ESPRESSO spectrograph (APSU: Anamorphic Pupil-Slicer Unit, BCA: Blue Camera, BTM: Blue Transfer Mirror, BXD: Blue Cross-Dispenser, CM: Main Collimator, DC: Dichroic, EG: Echelle Grating, FL: Field Lens, PM: Field Mirror, RCA: Red Camera, RTM: Red Transfer Mirror, RXD: Red Cross-Dispenser).

ics) took place in July 2013. ESPRESSO's aimed precision of 10 cm s^{-1} rms requires measuring spectral line position changes of 2 nm (physical) in the CCD plane, equivalent to only 4 times the silicon lattice constant! For better stability and thermal-expansion matching the CCD package is made of silicon carbide. The package of the CCDs, the surrounding mechanics and precision temperature control inside the cryostat head and its cooling system, as well as the thermal stability and the homogeneous dissipation of the heat locally produced in the CCDs during operation are of critical importance. ESO has built therefore a new *superstable* cryostat that has already demonstrated excellent short-term stability. A breadboard of the concept is currently being tested and the results will drive the design of the final ESPRESSO detector system.

3.8 A laser frequency comb

In order to track possible residual instrumental drifts, ESPRESSO will implement the simultaneous reference technique (similarly to HARPS; see, e.g., Baranne et al. 1996), i.e. the spectrum of a spectral reference will be recorded simultaneously on the scientific detector. Nevertheless, all types of spectrographs need to be wavelength-calibrated in order to assign to each detector pixel the correct wavelength with a repeatability of the order of $\Delta\lambda/\lambda \approx$

10^{-10} . A necessary condition for this step is the availability of a suitable spectral wavelength reference. None of the currently used spectral sources (thorium argon spectral lamps, iodine cells, etc.) would provide a spectrum sufficiently wide, rich, stable and uniform for this purpose. Therefore, the baseline source for the calibration and simultaneous reference adopted for ESPRESSO is a laser frequency comb. The LFC presents all the characteristics indispensable for a precise wavelength calibration and provides a link to the frequency standard. The procurement of an LFC suited for ESPRESSO is going on and at the time of writing, placement of a contract for a LFC covering the full 380 - 760 nm range was imminent. In parallel, ESO has been developing such a source for HARPS, in collaboration with other institutes and industrial partners (Lo Curto et al. 2012). As a back-up solution and in order to minimize risks, also a stabilized Fabry-Pérot is currently also under development within the consortium.

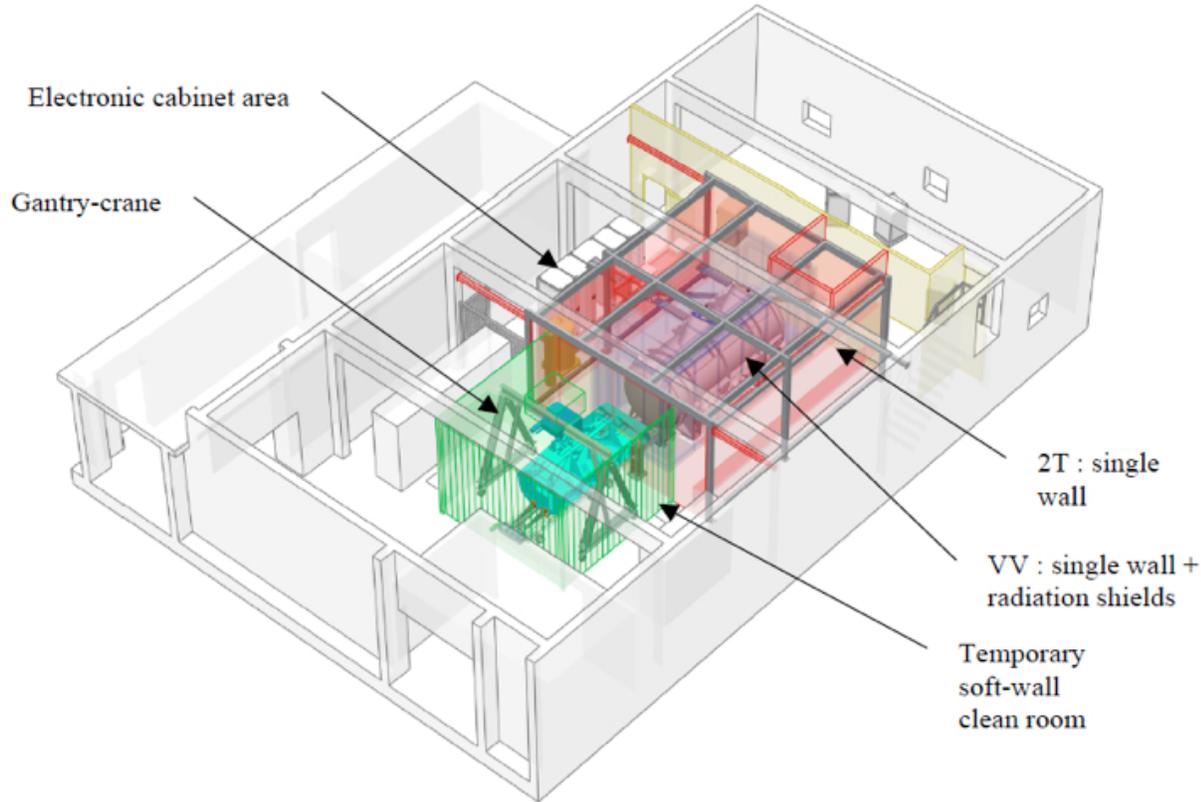


Fig. 15 ESPRESSO inside the CCL, vacuum vessel, and multi-shell thermal control system.

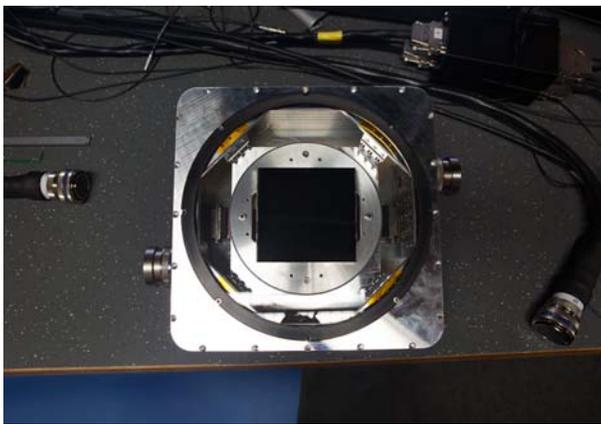


Fig. 16 The first ESPRESSO e2v CCD to be used in the cameras of the ESPRESSO instrument. These very large CCD samples have more than 80 million pixels over an area 92×92 millimetres.

4 ESPRESSO's data flow

Following the very positive experience gained with HARPS, ESPRESSO has been conceived since the beginning not to be a *simple* standalone instrument, but actually a *science-generating machine*. The final goal is to provide the user with scientific data as complete and precise as possible in a short time (within minutes) after the end of an observation, increasing in this way the overall efficiency and the ESPRESSO scientific output. For this purpose a software-

cycle integrated view, from the observation preparation through instrument operations and control to the data reduction and analysis has been adopted since the early phases of the project. Coupled with a careful design this will ensure optimal compatibility, easiness of operations and maintenance within the existing ESO Paranal Data Flow environment both in service and visitor mode. ESPRESSO Data Flow presents the following main subsystems:

- *The ESPRESSO Observation Preparation Software (EOPS)*: a dedicated visitor tool (able to communicate directly with the VOT - Visitor Observing Tool) to help the observer to prepare and schedule ESPRESSO observations at the telescope according to the needs of planet-search surveys. The tool will allow users to choose the targets best suited for a given night and to adjust the observation parameters in order to obtain the best possible quality of data.
- *The Data Analysis Software (DAS)*: dedicated data analysis software will allow to obtain the best scientific results from the observations directly at the telescope. A robust package of recipes tailored to ESPRESSO, taking full advantage of the existing ESO tools (based on CPL and fully compatible with Reflex), will address the most important science cases for ESPRESSO by analyzing (as automatically as possible) stars and quasar spectra (among others, tasks will be performed such as line Voigt-profile fitting, estimation of stellar atmospheric

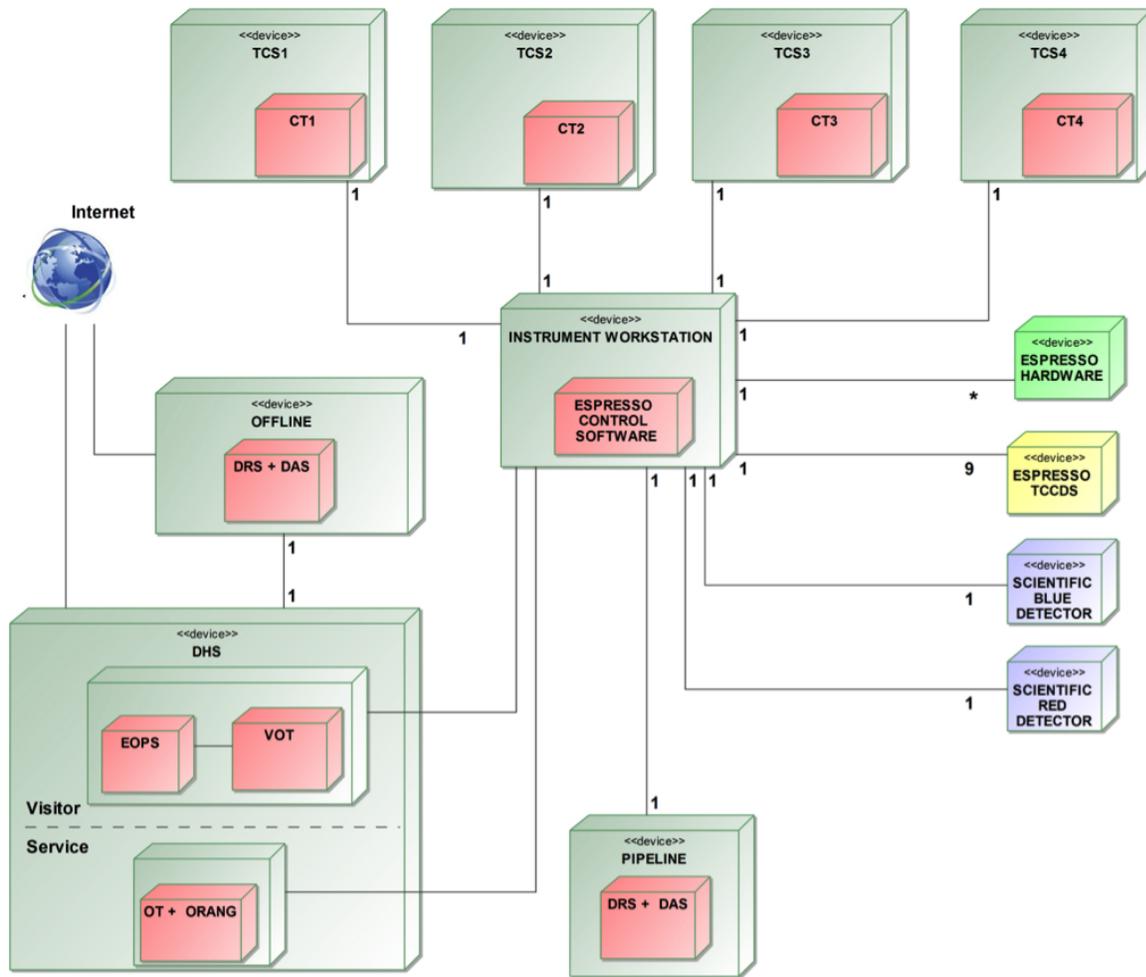


Fig. 17 Overview of ESPRESSO's control system.

parameters, quasar continuum fitting, identification of absorption systems).

- *The Data Reduction Software (DRS)*: ESPRESSO will have a fully automatic data reduction pipeline with the specific aim of delivering to the user high-quality reduced data, science ready, already in a short time after an observation has been performed. To this purpose the computation of the RV at a precision better than 10 cm/s will be an integral part of the DRS. Coupled with the need to optimally remove the instrument signature, to take account the complex spectral and multi-HDU FITS format, the handling of the simultaneous reference technique and the multi-UT mode will make the DRS a truly challenging component of the DFS chain.
- *Templates and control*: compared to other standalone instruments, the main reason for ESPRESSO acquisition and observation templates complexity will be the possible usage of any combination of UTs, besides the proper handling of the simultaneous reference technique. Coupled with the fact that at the instrument control level PLCs (Programmable Logical Controllers) and new COTS (Component Off-The Shelf) TCCDs will be adopted instead of the (old) VME technology,

ESPRESSO will contribute to open the new path for the control systems of future ESO instrumentation. A general overview of the ESPRESSO control system is shown in Fig. 17.

4.1 End-to-end operation

In the singleHR mode ESPRESSO can be fed by any of the four UTs, possibility which significantly improves the scheduling flexibility for ESPRESSO programmes and optimizes the use of VLT time in general. Scheduling flexibility is a fundamental advantage for survey programmes like RV searches for extrasolar planets or time-critical programmes like studies of transiting planets. The singleHR mode itself will thus greatly benefit from the implementation of the multiMR mode. The overall efficiency and the scientific output of long-lead programmes can be considerably increased if an integrated view of the operations is adopted. ESPRESSO shall not be considered as a stand-alone instrument but as a science-generating machine. Full integration of the data-flow system as described above is fundamental. ESPRESSO will deliver full-quality scientific data less than a minute after the end of an observation.

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