A new concept and a preliminary design for a high resolution (HR) and very-high resolution (VHR) spectrograph for the LBT

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Abstract. A way to fully exploit the large collecting area of modern 8–10m class telescopes is high resolution spectroscopy. Many astrophysical problems from planetary science to cosmology benefit from spectroscopic observations at the highest resolution currently achievable and would benefit from even higher resolutions. Indeed in the era of 8–10m class telescopes no longer the telescope collecting area but the size of the beam — which is related to the maximum size in which reflection gratings are manufactured — is what mainly limits the resolution. A resolution-slit product \(R_\varphi \approx 40,000\), is the maximum currently provided by a beam of 20 cm illuminating the largest grating mosaics. We present a conceptual design for a spectrograph with \(R_\varphi \approx 80,000\), i.e. twice as large as that of existing instruments. Examples of the possible exploitation of such a high \(R_\varphi\) value, including spectropolarimetry and very high resolution (\(R \sim 300,000\)), are discussed in detail. The new concept is illustrated through the specific case of a high resolution spectropolarimeter for the Large Binocular Telescope.

Key words: High resolution spectroscopy, instrumentation: optical spectrographs.

1. Introduction

The construction of 8–10m class telescopes has brought new opportunities for astrophysical research using high resolution spectroscopy. Over the last few years a number of spectrographs have been designed and manufactured for telescopes of this class, most of them with large optics, mosaic gratings, fast focal ratio cameras and large area CCD detectors (e.g. Pilachowski et al. 1995). Large telescopes allow us to extend high resolution spectroscopy to weaker sources, but a number of problems arise from the related larger beam diameters. Such problems are related to the demand for higher stability, good velocity accuracy and careful attention to the instrumental profile.

The above demand has been fulfilled via new spectrograph concepts such as \textit{white pupil} design, immersed gratings, active pupil correction and larger refractive or catadioptric cameras. The performances of such spectrographs are always a compromise between resolution, throughput, and spectral coverage.

The dispersing element adopted in all high resolution spectrographs studied or built so far is the \textit{echelle} reflection grating. From diffraction theory (e.g. Schroeder, 2000) we know that the resolution of a conventional echelle spectrograph in Littrow configuration is given by the \textit{resolution-slit product}:

\[
R_\varphi = 2(d/D) \tan \delta
\]

where \(R\) is the resolution, \(\varphi\) is the angular slit width on the sky (as seen by the telescope), \(d\) is the beam diameter at the collimator, \(D\) is the telescope diameter and \(\delta\) is the blaze angle, i.e., the angle between the facet and the grating normals.

Modern high resolution spectrographs for 8–10m class telescopes have a maximum resolution-slit product of about 40,000 arcsec. Such a number comes from state-of-the-art technology in optical component manufacturing. The straightforward way to increase the \textit{resolution-slit product}, for a telescope of a given aperture \(D\), is to increase the blaze angle \(\delta\) and/or the beam diameter \(d\). R4 echelles, corresponding to \(\delta = 76^\circ\), are the most tilted gratings currently manufactured. Construction difficulties prevent larger blaze angles and large beam diameters as well, not to talk about costs. Indeed the beam diameter is limited by the maximum dimensions of the grooves area in currently available ruling engines, i.e. about 20 cm. Other ways have to be explored to further increase resolution.

In this paper we propose a new optical concept based on the use of two R4 echelle reflection gratings allowing
us to double the currently achievable $R \varphi$ values. Cross-dispersion by means of high efficiency volume phase holographic (VPH) gratings is used to compensate for the reduced efficiency of using two echelle gratings. This concept will be illustrated in the case of a high-resolution (HR) and very-high resolution (VHR) spectrograph proposed for the Large Binocular Telescope (LBT).

2. Scientific motivations for HR and VHR spectroscopy

High resolution spectroscopy (i.e. spectroscopy at resolving powers of $R \sim 40,000$ or higher) is a fundamental tool to derive physical information about cosmic sources, both galactic and extragalactic. The optical spectra of astrophysical objects can provide, if observed at high resolution and high $S/N$, detailed information on many important physical quantities such as chemical abundances and their ratios, radial and rotations velocities, convective motions, pulsations, mass losses, magnetic fields, and many others (see the proceedings of the Workshop on “High-Resolution Spectroscopy with Very Large Telescopes”, Kraft 1995, and reference therein). Until recently, the biggest limitation to high resolution spectroscopy has been the small aperture of the available telescopes, which limited HR spectroscopy mostly to stellar physics and relatively bright objects. With the advent of 8–10m class telescopes, equipped with HR cross-dispersed echelle spectrographs and sensitive CCD detectors, it is now possible to extend the realm of HR spectroscopy to much fainter stars and to extragalactic sources as well. Moreover, the large aperture of the current and future telescopes allows a further step forward in resolution, opening up the possibility of very high resolution (at resolving power of several 100,000) for objects well beyond the brightest and closest stars.

HR spectrographs working at resolutions of 40,000–100,000 on 8–10m class telescopes (as well as on 4m class telescopes for brighter objects) have already demonstrated the power of HR spectroscopy in many different research areas. Stellar objects remain the most easily accessible targets, but absorption lines in QSOs and distant galaxies have also become observable, at least for the brightest of these objects, thus providing information on the intergalactic medium and absorbing material along the line of sight (e.g. Shull 1995). High resolution is needed to resolve the complex velocity fields of the intervening gas, while the need for high throughput is dictated by the faintness of most extragalactic objects.

HR is also crucial to resolve the velocity structure of interstellar medium clouds in our Galaxy (e.g. Kennicutt et al. 1995), as well as to determine the $^{6}\text{Li}/^{7}\text{Li}$ isotope ratio in the ISM, a fundamental parameter to investigate the production of Li by cosmic rays during galactic evolution. With large aperture telescopes, it is now possible to investigate the ISM throughout the Galaxy and in many different directions.

Abundance determinations in stars of different populations remain a fundamental tool to study stellar evolution and the formation of the galactic disk, of the bulge and of the halo (e.g. Sneden et al. 1995). Although abundance determinations can be made in some cases through equivalent widths rather than line profiles, high resolution is required in many cases to resolve blends and for accurate matching of the observed line profiles with synthetic ones. Chemical abundances and their ratios, as well as isotopic ratios, provide information on internal mixing in stars and put stringent constraints on models of stellar structure and evolution. Observations of open and globular clusters, i.e. of homogeneous samples of stars with the same age and chemical composition, allow tracing galactic evolution for different stellar populations and in different parts of the Galaxy. Determinations of the Li and Be abundance in stars allow investigating stellar interior mixing processes as well as primordial nucleosynthesis and Li enrichment throughout the history of our Galaxy (Pinsonneault 1997).

The determination of accurate line profiles in the spectra of stars allow studying the velocity fields in stellar atmospheres produced by the interaction of convection and rotation and/or stellar oscillation. Line profiles (e.g. Demarque 1995), asymmetries and shifts and line bisectors observed at high resolution and high $S/N$ in late-type stars allow us to derive information on convective motions generated in subphotospheric convective zones (Gray 1992). They also provide information on winds and mass losses in hot stars and in late-type giants and supergiants. Accurate line profiles also allow us to measure magnetic fields (through the Zeeman effect) and to infer the presence of magnetic surface structures line spots and plage (through Doppler imaging techniques, e.g. Vogt & Penrod 1983).

Finally, the determination of precise radial velocities by means of HR spectroscopy allow us to search for planets orbiting nearby stars, as well to determine stellar pulsations and oscillations (e.g. Queloz 2001). The field of stellar asteroseismology of solar type stars is still in its infancy but it is expected to grow enormously with the advent of high stability HR spectroscopic facilities at large telescopes. However asteroseismology of other classes of objects such as white dwarfs, $\beta$ Cephei or $\delta$ Scuti stars is an established science and benefits of well developed methods, procedures and interpretative models based on HR spectroscopy data (e.g. Zerbi 2000). The existence of planetary size bodies orbiting nearby stars has been clearly demonstrated on the basis of accurate radial velocity measurements, but much remain to be done for understanding the formation of planets and planetary systems other than our own.

To study velocity fields in stellar atmospheres as well as to study isotope ratios and velocity fields in the ISM, spectral resolutions around 100,000 are often insufficient. Resolutions at least a factor 2 or 3 higher are desirable together with high throughput of the telescope-spectrograph combination. The large aperture of 8-10m
Gemini South. They provide UVES at VLT, HRS at HET, HDS at Subaru, HROS at large telescopes (diameter 8–10m): HIRES at Keck, Five high resolution cross-dispersed echelle spectrographs: Rϕ \approx 300,000) on an 8m class telescope would be a unique instrument, not yet available at any large telescope in the world. From line profiles, asymmetries and shifts measured by such an instrument, we could address the physical properties of convection, rotation, magnetism, stellar activity and stellar seismology at a level of detail so far possible only in the case of the Sun. Fields such as asteroseismology of solar-type stars, detection of extra solar planets and the study of the interstellar medium are all expected to greatly benefit from VHR spectroscopy. The possibility of analysing the light of celestial sources in their different polarization components offers the further advantage of studying the central role of magnetic fields in astrophysics. Under this respect, coupling a HR spectrograph with a polarimetric unit is the only way to understand the structure and dynamics of surface magnetic fields for a variey of objects, ranging from late-type stars to young stellar objects, from accretion sources in close binaries to QSOs and AGNs (Strassmeier et al. 2001). The spectrograph we will discuss in the following sections offer these various capabilities, including a range of possible resolutions (from HR to VHR) as well polarimetric capabilities.

3. High resolution spectrographs and their limitations

3.1. Overview of existing instruments

Five high resolution cross-dispersed echelle spectrographs are currently operative or under construction at large telescopes (diameter 8–10m): HIRES at Keck, UVES at VLT, HRS at HET, HDS at Subaru, HROS at Gemini South. They provide Rϕ products of \sim 40,000 and maximum resolutions, with lower efficiency, of \sim 100,000 or slightly higher using image slicers. Their characteristics are summarized in Table 1.

Two of the instruments in Table 1 (UVES at VLT and HRS at HET) are based on the white pupil design. The white pupil concept has been introduced by Baranne (1972) and elaborated by Delabre for UVES (Dekker et al. 2000). This configuration eliminates vignetting and aberrations by re-imaging the pupil at the echelle onto the camera pupil, where the cross disperser is located (see Figure 1). With few added optical elements, providing only a few percent of light-loss, the vignetting typical of traditional designs is removed and the image quality and overall luminosity substantially enhanced.

UVES (UV–Visual Echelle Spectrograph) for the ESO Very Large Telescope is based on a 1x2 mosaic R4 echelle that provides Rϕ \sim 40,000 with a beam size of 200 mm. The steep angle of the R4 grating requires minimizing the angle between camera and collimator to preserve the efficiency of the grating. UVES is mounted at an f/15 Nasmyth focus of unit UT2 (Kueyen) of the VLT. It has two arms, a red one (420–1100 nm) and a blue one (300–500 nm) to optimize efficiency. Many pre-slit optical systems are common to the two arms (image derotator, ADC, depolarizer, dichroic, image slicers, I2 cell). The two arms have the same optical design: a main off-axis parabolic collimator is used in double pass once to collimate the beam on the grating and a second time to reform an intermediate spectrum very near the slit location. A second identical collimator cancels the off-axis aberration of the first one and casts a white pupil onto the cross disperser.

Since the camera aperture in UVES is relatively small, there is no need for very fast focal ratios for the cameras: f/1.8 for the blue one and f/2.5 for the red one. Rϕ = 41, 400 (38,700) in the blue (red) domain allows a maximum resolution of 80,000 (110,000) with a 0.4 (0.3) arcsec slit. UVES is equipped with a 2Kx4K EEV CCD in the blue, and a mosaic of two different (EEV and MIT/LL 2Kx2K) CCDs in the red. With a S/N=10 per wavelength bin, for a 1 hr exposure, seeing = 0.7 arcsec, limiting magnitude at R=60,000 is V=19.0 (red) and U=17.5 (blue). Using the iodine cell the velocity accuracy is 47 m/s (35 m/s) in the blue (red) domain. A performance comparison in terms of efficiency, spectral coverage and resolution indicates that UVES is the most advanced spectrograph available at present.

Another high resolution white pupil spectrograph is the High Resolution Spectrograph (HRS, Tull 1998) at the 9m Hobby-Eberly Telescope, that is essentially an arm of the UVES design. It is fed from the f/1.8 primary focus with fibers and it is mounted on an optical bench,
allowing high stability. It has a 200 mm beam diameter and an off-axis parabolic collimator in white pupil configuration. Its R4 1x2 mosaic echelle is identical to the UVES red one. Its $R \varphi = 30,000$ should allow reaching a limiting magnitude $V=19.4$ at $R=60,000$, with a S/N=10 in 1 hr exposure. However actual measurements [http://rhea.as.utexas.edu/HET_hrs.html] show that the limiting magnitude is 2.5 mag lower.

HIRES (High Resolution Spectrograph, Vogt et al. 1994) is operative since 1993 at the Keck I telescope. In HIRES the light enters the slit from the Keck f/13.7 Nasmyth focus, is collimated by a spherical reflective collimator to form a 305 mm beam that is directed to a 1x3 320x1270 mm$^2$ mosaic R2.8 echelle, mounted on a granite substrate. The beam is then cross-dispersed by a low-order grating and fed into an f/1.0 catadioptric camera with 0.75 m of clear aperture that provides excellent image quality from 0.31 to 1.1 $\mu$m over the full 6.7° camera field of view. In spite of its $R \varphi = 39,000$, maximum resolution is limited to 67,000, by the 2Kx2K 24 $\mu$m pixel CCD. For a S/N ratio of 10, a 1 hr exposure at $R=60,000$ gives $V=19.7$.

HDS, the High Dispersion Spectrograph for the Subaru Telescope (Noguchi et al. 1998) is very similar to HIRES, with a slightly higher image quality and a smaller pixel size, ensuring better spectral resolution. This instrument has entered in operation in April 2001 and the limiting magnitude is given as $V=18.6$ in 1 hour at S/N=10.

HROS, the High Resolution Optical Spectrograph (D’Arrigo et al. 2000) for Gemini South, makes use of an immersed echelle grating (Szumski & Walker 1999) in order to decrease overall size and weight, since the instrument will be mounted at the Cassegrain focus through a pre-slit prism focal modifier. The R2 echelle is immersed into a high refraction index medium. If we call n such an index, the resolution of the immersed grating is n times higher than conventional reflection gratings. With a $R \varphi = 28500$, HROS is capable of a maximum resolution of 75,000. However, the instrument design is not yet finalised since stability problems at the Cassegrain focus may eventually lead to modifications of the current design.

### 3.2. Limits of existing configurations

As stated in the introduction, existing high resolution spectrographs are limited by the $R \varphi$ they can provide, i.e. about 40,000 for an 8m class telescope. For a given $R \varphi$ and a given echelle grating the only way to increase the resolution is to narrow the entrance slit of the spectrograph. A narrower slit however reduces the instrumental throughput and requires an adequate sampling. For instance, an instrument with an $R \varphi = 40,000$ can be operated at $R = 200,000$ provided a slit of $\varphi = 0.2$ arcsec is used. The problem is that the slit dimension prevents most of the source light to enter the spectrograph, even in good seeing conditions.

It is possible to overcome this problem by using either image slicers or adaptive optics (AO). Image slicers are the most widely used devices to allow spectrographs to be operated at high resolution with acceptable throughput. With the use of an image slicer the resolution in the spectrographs reviewed above can be pushed up to about $R \approx 120,000$ (160,000 for HDS, see Table 1). The use of adaptive optics to increase the slit throughput is instead the object of recent studies (Wiedemann et al. 2000, Pallavicini 2001) and has found so far only limited
practical application in the optical (Ge et al. 1999). We will come back to this possibility later on.

Since the dimensions of the CCD detector are limited, increasing the resolution of a spectrograph by narrowing the entrance slit also reduces the available spectral coverage in a single exposure. In the example used above, i.e. a spectrograph with \( R = 40,000 \) operated at \( R = 200,000 \), the projected slit image will cover a \( \delta \lambda = 0.004 \text{ nm} \) at 800 nm, and will have to be sampled with at least 2.5 pixels. Assuming a CCD with 15 \( \mu \text{m} \) pixels, we obtain a reciprocal dispersion of 0.11 nm/mm. For a 4Kx4K CCD (typical of existing spectrographs), one order will cover 5.5 nm at 800 nm. If we want to cover the range between 500 and 1000 nm \(^\dagger\), we will need (approximately) 100 orders. In order to accommodate 100 orders on the CCD, assuming an order separation of the same size of the spectrum, the slit height is limited to 1/200 of the CCD height, i.e., each spectrum has a maximum allowed height of 307 \( \mu \text{m} \) corresponding to about 1.4 arcsec at the slit location. Such a figure might not be a problem for a fiber-fed spectrograph where the core radius of the fiber corresponds to the slit height but it is certainly a problem for direct-feed spectrographs or for instruments equipped with image slicers. In order to cover 500-1000 nm at higher resolutions we will be forced to either increase the CCD dimensions, or to reduce the available spectral range in a single exposure.

Both the spectral coverage and throughput problems would be alleviated by increasing the \( R \phi \) product. For example, a \( R \phi \simeq 80,000 \) spectrograph could be operated at \( R = 200,000 \) with a 0.4 arcsec entrance slit (instead of 0.2) with an evident gain in throughput. The portion of spectrum covered by each order remains unchanged since the free spectral range is the same. However, the height of the spectrum in each order and the inter-order separation is decreased allowing to optimize the CCD filling. In the case, for example, of a 10 arcsec slit-height, in the \( R \phi = 40,000 \) configuration the spectrum height is 125 pixels while in the \( R \phi = 80,000 \) setup the height is reduced to one half of it, i.e. to 62.5 pixels, thus allowing to cover a spectral range twice as large in a single exposure.

4. A new concept

A way to increase \( R \phi \) without increasing the size of the beam and/or the grating blaze angle is represented by the use of 2 echelle gratings mounted “in series”, in order to increase angular dispersion. Such an idea has been already used in the MEGA monochromator (Engman & Lindblom 1984). MEGA, built with \( R \) about 2,000,000 using four echelles, was not conceived for astronomical use and hence was not optimized for efficiency. The concept however is suitable to be optimized for astronomical use and to be combined with the white-pupil design taking advantage of the optical quality given by such configuration. In the following section we present a triple pupil configuration accommodating two R4 echelle gratings and volume phase holographic (VPH) gratings as cross-dispersers, capable of providing a \( R \phi \) of the order of 80,000 with a beam size similar to that of UVES, i.e. 20 cm.

We present a preliminary study of the above concept for application to the Large Binocular Telescope (LBT). This telescope, for which no high resolution optical spectrograph has yet been selected, will be the largest single telescope in the coming years. The unprecedented throughput of LBT will allow us to extend high-resolution (HR) spectroscopy to weaker sources and to perform very-high-resolution (VHR) spectroscopy of a significant number of astronomical objects.

The Large Binocular Telescope (Hill & Salinari 1998) has two Gregorian f/15 identical primaries of 8.4 m diameter, mounted on the single structure. The LBT is expected to see first light through the first mirror in 2004 and through the second mirror one year later. First light instruments include imagers and low resolution spectrographs both for visible and IR wavelengths (LUCIFER, MODS, LBT Large Binocular Camera). A HR optical spectrograph is not foreseen for first light, but the LBT Science Advisory Committee recognized the importance of such an instrument either as a second generation or as visitor instrument.

The parameters space we intend to explore (\( R \sim 40,000-300,000 \)) requires highly stabilized and thermalized environment and demands an instrument mechanically detached from the structure. Within the various configurations offered at the LBT for a HR spectrograph (Pallavicini 2001), the most promising is to position a fiber feeding unit at each of the two direct Gregorian foci and lead a fiber bundle out of the LBT structure to the fixed location of the spectrograph.

Such a configuration allows us to process the light before fiber feeding via a fore-optics of limited dimensions. This is the case of the spectropolarimeter PEPSI proposed by Strassmeier (2001). Each Gregorian focus feeds a removable polarimeter measuring two independent polarizations, either circular or linear (see Fig. [3]). Integral light can be measured bypassing the polarimeters. In either case, four spectra per echelle order are recorded on the detector (e.g. 2 circular polarizations + 2 linear polarizations or 2 star spectra + sky + wavelength reference spectrum). Such assembly takes full profit of the double pupil configuration of the LBT and can provide a high resolution spectro-polarimeter of unprecedented performances. We emphasize that no high resolution spectro-polarimeter currently exists on 8–10m class telescopes, although the possibility of implementing such a polarimeter was considered for HROS.

Another advantage of the fiber feeding at both Gregorian foci is the possibility to use the LBT advanced optics. LBT will be equipped with adaptive secondary mirrors providing AO correction at the same Gregorian

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\(^\dagger\) this will be the spectral range we are interested in for the proposed instrument at the LBT.
focal stations. Pallavicini (2001) proposed a very high resolution spectrograph \((R > 250,000)\) based on the enhanced throughput in a narrower slit provided by the AO correction. No spectrograph at present (except UHRF at the 4m AAT, Diego et al. 1995) is able to reach such a high spectral resolution.

The triple-white-pupil double-echelle \(R_\varphi \sim 80,000\) spectrograph we propose combines the performances of both the above configurations. In the following sections we examine in some details the characteristics of such a spectrograph.

5. Preliminary design of a HR and VHR spectrograph for the LBT

5.1. Optical design

We start from the classical double white pupil configuration, shown in Figures 1 and 2, e.g. used in UVES. Such a configuration forms a first white pupil at the location of the echelle via an off-axis parabola. The dispersed light is then focused to an intermediate spectrum close to the slit location via a second passage through the same off-axis parabola and then re-collimated by another off-axis parabola to reform a second white pupil where the cross-disperser is located. The light is then focused by a camera with suitable characteristics onto the CCD.

The first modification occurs at the cross-disperser where in our design the second R4 echelle is positioned with a small off-plane angle (see Figures 3, 4 and 5). After being diffracted by the second R4 grating the light passes again at the second parabola and a second intermediate spectrum is reformed near the slit location. The light is then collimated by a third off-axis parabola to reform a third white pupil where the cross-disperser is located, corresponding to the entrance pupil of an all-refractive camera.

Due to the high anamorphic effect, in Littrow mode we have to limit the beam diameter to about 160 mm if we don’t want to vignette the dispersed beam from the first echelle on the second one: this limits \(R_\varphi\) to \(\sim 65,000\). However a slight off-Littrow angle, the same for both echelles, allows us to increase \(R_\varphi\) further. One degree off-littrow allows reaching \(R_\varphi \approx 78,000\).

With regard to the echelles, we choose two R4 12.9 gr/mm gratings, with 1° off-Littrow and 0.2° off-plane. The wavelength range from 500 to 1000 nm (1) is covered in 150 orders, from the 300th to the 150th order. Due to off-Littrow configuration, some additional efficiency losses reduce total echelles efficiency about 0.30 at blaze peak.

\[ m \lambda_{b,1} = 2 \sigma \sin \delta \cos \theta_1 \quad \text{and} \quad m \lambda_{b,2} = 2 \sigma \sin \delta \cos \theta_2 \]

where \(\theta_1\) are the off-Littrow angles) the blaze wavelengths are the same at any order only if off-Littrow angles are the same, too.

To counterbalance the lower efficiency of the two echelles configuration as compared to one echelle, the cross-disperser efficiency must be as high as possible. Prisms have too low angular dispersion. Instead of more common surface-relief reflection gratings, we can use volume phase holographic (VPH) gratings, which provide measured efficiencies up to 95%. However we assume a conservative value about 0.90. VPH gratings and their astronomical use are illustrated by Barden et al. (1998).

The two echelles configuration provides an additional interesting operation mode: a lower resolution mode \((R_\varphi \approx 40,000)\) obtained by tilting the folding mirror near the slit to exclude one grating from the optical path. In this mode, after passing on the first echelle, the beam from M1 is redirected towards M3, creating a white-pupil directly onto the cross disperser.

5.2. Fiber feed and adaptive optics

Since high stability is a primary requirement, the spectrograph will be bench mounted and fed with fibers. In order to reduce focal ratio degradation, the fibers cannot be fed directly by the f/15 Gregorian focus. Using microlenses to modify the focal ratio to f/5, the scale at the fiber entrance is 204 \(\mu\)m/arcsec. Two standard fiber core diameters have been selected, 200 \(\mu\)m and 50 \(\mu\)m, corresponding to 1 arcsec and 0.25 arcsec, respectively. The median seeing at Mt Graham is about 0.7 arcsec, and 200 \(\mu\)m fibers are well matched to the seeing, carrying most of the light from the star with little sky contamination. The smaller fibers are intended to be used with AO correction for the VHR mode. Since the spectrograph is designed at f/10 the fibers need also exit microlenses to match the aperture.

When used with the polarimetric units, the spectrograph will receive 2 fibers per Gregorian mirror carrying the pre-processed light. Four spectra per echelle order have then to be recorded simultaneously on the CCD. When used instead in integral light, the light from the star can be directed into two fibers, one for each telescope. The other two fibers can be used respectively for the sky and for a wavelength reference spectrum. In this configuration and assuming the 1 arcsec fibers, the minimum interorder separation must be about 8 arcsec. This interorder separation is too small for use of Bowen & Walraven image slicers, because these IIs put the slices side by side along the slit direction. Adaptive Optics is therefore the only viable solution for a VHR mode in this spectrograph.

5.3. Cameras, detector and spectral format

The design of the camera has to take into account the required sampling that is linked to the fore-optics characteristics and ultimately to the fiber core dimensions. It is linked as well to the range in spectral resolutions one plans to have in the spectrograph for each mode, e.g. AO or polarimetric mode. In the specific case we designed two cameras, one to span resolutions from 40,000...
Fig. 3. **Triple white pupil: schematic design.** A first echelle is located in the first white pupil. Two transfer collimators reform a second white pupil on the second echelle, and another similar system reforms a third white pupil on the cross disperser. In our design a parabolic off-axis mirror M1 acts like collimator and 1\textsuperscript{st} transfer collimator, a second mirror M2 acts like 2\textsuperscript{nd} and 3\textsuperscript{rd} TC, and a third mirror M3 acts like 4\textsuperscript{th} TC.

Fig. 4. **New concept high resolution spectrograph: optical layout.** Light from the slit (located near the center of the figure, see insert) is collimated from paraboloid M1 onto the echelle 1. After diffraction, the beam is refocused again by M1 near the slit position, where a folding mirror reflects it again towards M2. It reforms a white pupil where the echelle 2 is located. The beam is diffracted in such a manner as to double its angular dispersion. M2 and the other paraboloid M3 reforms another white pupil for positioning the cross disperser, and finally the beam is focused by a camera (in this design the short camera is shown).

to 160,000 and a second one for very high resolutions (up to 320,000). The short camera has a focal ratio f/3.0 and a focal length of 604 mm (see Figure 8). The long camera has a focal ratio f/4.9 and a focal length of 1220 mm. There is no vignetting with the external focus. The efficiency of both cameras has been estimated to be about 0.90 (10 air-glass interfaces).

The evolution of CCD arrays suitable for astronomical instruments is very fast. Only preliminary considerations can be drawn about these components at this stage, likely to be modified during the final design and manufacturing phase. As an example we have selected a detector with a pixel size 15 \(\mu\text{m}\), with QE similar to the Marconi deep-depleted fringing-free CCDs. This chip has a QE > 40% in the wavelength range 400-900 nm with a maximum QE \(\geq 90\%\) at 600 nm. A 4Kx4K (mosaic) chip of this kind will be needed together with the short camera and resolution up to 160,000; a mosaic of two 4Kx4K chips will be needed in the spectrograph detector head for the highest resolution.

The short camera provides a slit sampling of 3 pixels per 0.4 arcsec (corresponding to a maximum resolution of 200,000) at blaze peak. This is a minimal requirement because a lower sampling (e.g. 2 pixels per 0.4 arcsec) would lead to undersampling in the blue part of each order, due to the anamorphic magnification (caused by the two off-Littrow echelles) on the projected slit width.
With the long camera, the slit sampling is 3 pixels per 0.2 arcsec.

Assuming 8 arcsec minimum interorder separation, due to the four spectra per order, from 30 to 45 orders can be accommodated in a 4Kx4K 15 µm CCD. Thus 4 exposures are needed to cover the whole spectrum. Each set of orders corresponds to a different cross disperser, optimized for that wavelength range. In Figure 7 a typical spectral format with 30 orders is shown.

With the long camera the spectrum must be recorded on a 8Kx4K CCD mosaic. The use of only one 8Kx4K CCD mosaic with both cameras would be advisable, using only one half of the CCD area with the short camera. In this case, a mechanical system is required for switching between the two cameras.

5.4. Image Quality

The whole optical system described above has been optimized taking simultaneously into account all possible configurations, i.e. the 4 different cross dispersers each coupled with the short or the long camera. The optimization has been compute for 45 wavelengths throughout the spectral range of the instrument. Typical RMS spot radii are about 10-15 µm and the radius corresponding to 80% encircled energy is less than 15 µm (1 pixel) for many wavelengths and configurations.

In Figure 8 we show spot diagrams for five different orders at the blaze peak (second column) and at the borders of the corresponding orders (first and third columns). Only at the borders of few orders image quality degrades the maximum resolution.

5.5. Observing modes

This spectrograph has been designed to provide two main observing modes: a) High Resolution mode; b) Very High Resolution mode. The former uses the larger core-radius fiber bundle and no AO correction. The latter instead uses the AO correction and the smaller core-radius fiber bundle. Each mode has two sub-modes depending on whether one or two echelles are inserted in the beam. In the former case (HR mode) two resolutions are available, \( R = 40,000 \) and \( R = 80,000 \). In the latter case (VHR mode) \( R = 160,000 \) and \( R = 320,000 \). In principle the polarimeter can be used in both the HR and VHR modes, however the small fraction of polarized light in many cases would make its use in the VHR mode limited to extremely bright objects and hence of limited interest.

At this level of the design the use of other fiber sizes to operate the spectrograph at different (or higher) resolutions can not be excluded. For instance 40 µm fibers corresponding to 0.2 arcsec on the sky would provide a maximum resolution of about 390,000 in the mode with \( R_{\varphi} = 78,000 \). The observing modes and sub-modes described above are summarized in Table 2.

5.6. Mechanical Concept

A possible application of the spectrograph described in these pages, in fact the one that triggered this study, is its use as part of the spectropolarimeter PEPSI (Strassmeier et al. 2001) at the LBT. At the level of the present study the mechanical assembly of the spectrograph has only been sketched conceptually and we briefly summarize here the concept. Indeed the final details of such a design can only be fixed in a phase closer to procurement and realization.
Table 2. Observing modes: two main modes are available, an High Resolution (HR) mode, and a Very High Resolution (VHR) mode. In HR mode, with 200 µm fibers and without AO, resolutions up to 80,000 are available, while in VHR mode, with 50 µm fibers and AO, resolutions up to 320,000 are available.

| Mode          | number of echelles | fiber size (µm) | AO | camera | detector | Resolution |
|---------------|-------------------|----------------|----|--------|----------|------------|
| HR (with or w/o polarimeter) | 1                | 200 (1)        | OFF | short  | 4Kx4K    | 40,000     |
|               | 2                | 200 (1)        | OFF | short  | 4Kx4K    | 80,000     |
| VHR (no polarimeter) | 1                | 50 (0.25)      | ON  | short  | 4Kx4K    | 160,000    |
|               | 2                | 50 (0.25)      | ON  | long   | 8Kx4K    | 320,000    |

Due to the requirement of thermal and mechanical stability it is convenient to have the spectrograph detached from any telescope movable part. The LBT provides an interesting possible location in the inner part of the concrete pillar that supports the telescope main structure. The inner part consists in a cylindrical room of about 9 m diameter, accessible by stairs and elevator, equipped with a crane and suitable for a remote instrument location.

At this location the optical components of the spectrograph will be mounted with adjustable supports on an anti-vibration optical bench of suitable size. The bench itself will be selected in order to provide the needed mechanical stability. The upper part of the bench will be covered with a closure to create a thermal controlled environment in order to guarantee the needed thermal stability.

The proposed design makes use of a limited number of movable parts. Indeed with the exception of the flip mirror allowing to switch between the polarimetric and the integral light modes and of a small folding mirror to toggle between the single-echelle and the double-echelle modes, the main spectrograph optics (off-axis parabolae and gratings) have no movable parts. However each of these components has to be finely adjusted during instrument integration and their supports designed accordingly.

Two main movable subsystems will instead have to be implemented, one before and one after the main spectrograph optics. First the light that feeds the spectrograph is carried by different fiber bundles depending on the observational mode. A mechanism to change the bundles must then be implemented in front of the spectrograph. Second the full spectral range of the spectrograph requires more than one cross disperser and this demands an exchange mechanism for these components after the main spectrograph optics.

Depending on the observing mode the spectrograph needs either the long or the short camera. These subsystems can be exchanged automatically by an exchange mechanism or manually at day time. The former solution allows the rapid change between the corresponding observing modes but requires high precision mechanics and has a relevant impact on the cost of the instrument. The latter does not allow such toggling but is more economic and eventually more reliable.

Table 3. Total throughput for PEPSI.

| λ (nm)     | Total throughput |
|------------|------------------|
|            | 550 | 700 | 850 |
| Optics     | 0.79 | 0.79 | 0.79 |
| echelles   | 0.30 | 0.30 | 0.30 |
| VPH cross disp. | 0.92 | 0.91 | 0.92 |
| CCD QE     | 0.92 | 0.87 | 0.57 |
| telescope  | 0.75 | 0.75 | 0.75 |
| fibers     | 0.80 | 0.80 | 0.80 |
| total      | 0.12 | 0.11 | 0.07 |

In HR mode at R=60,000 (this resolution, not present in our design, is chosen for comparison with the other high resolution spectrographs) the limiting magnitude in integral light is V=20.2 for S/N=10 per resolution element in 1 hour (other assumptions are: 1x1 binning, RON 3 electrons rms per pixel, dark noise 1 e⁻/pixel/hr, sky background 22 mag/arcsec², seeing 0.7 arcsec).
Fig. 9. Schematic design of the PEPSI instrument at the Large Binocular Telescope.

With the same assumptions and considering an AO system capable of concentrating 70% of the light into a 0.25 arcsec fiber, in VHR mode at R=320,000 limiting magnitude is V=18.6.

A comparison of the performances of PEPSI with those of the other HR spectrographs on 8–10m telescopes is made in Table 1.

6. Conclusions

We have presented in these pages a conceptual design for a versatile high resolution spectrograph. On the core idea of providing a resolution-slit product twice that of existing facilities (80,000 instead of 40,000) with a beam size no larger than in the latter cases, we designed an instrument capable of covering resolutions from 40,000 to 320,000 with suitable sampling and high throughput.

The innovation in the optical concept resides in the use of two R4 echelle grating “in series” in a white-pupil configuration and compensates for the low efficiency of this configuration by using Volume Phase Holographic gratings as cross dispersers.

We have applied the above concept to a fiber-fed bench-mounted spectropolarimeter proposed for the Large Binocular Telescope. In the non-AO mode, light from the two Gregorian foci of the LBT is preprocessed by two identical polarimetric units (one for each telescope) which feed by means of a bundle of optical fibers a high-stability thermally controlled spectrograph mounted on a bench in the telescope pillar. A cross-dispersed spectrum with four spectra per order, corresponding to different polarization modes, with a minimum separation of 8 arcsec between different orders, is recorded on a 4K×4K CCD detector. The full spectral range between 500 and 1000 nm can be covered in four exposures. A lower resolution mode (R~40,000) which makes use of only one echelle can be implemented in the same configuration. The polarimetric units can be either inserted or removed from the optical path. In the latter case, two spectra of the same object (one for each telescope) plus sky and a wavelength reference source are obtained in each exposure.

By using AO and a slit of 0.25 arcsec, a very-high-resolution non-polarimetric mode capable of a maximum resolution of ~320,000 can also be implemented using a second long camera and a mosaics of two 4k×4K CCD detectors. This resolution is currently not available at any 8–10m class telescope. By using only one of the two echelles, a maximum resolution of ~160,000 can be obtained with the short camera and the same 4k×4K CCD detector used in the polarimetric mode. The short and long camera are interchangeable, either automatically or
Fig. 6. Short camera: f/3.0, focal length 604 mm. The last lens is the dewar window before the CCD. Three different wavelengths belonging to the same echelle order are shown. Beam diameter and the related focal ratio are wavelength-dependent.

manually. Different fiber sizes (from 200 to 50 µm) will be used in the HR (polarimetric) mode and in the VHR (adaptive optics) mode, respectively.

In its combination of polarimetric capabilities and very-high resolution modes the proposed instrument will be unique on 8-10m class telescopes and will allow addressing a large variety of astrophysical problems, ranging from nearby stars to distant quasars.

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Fig. 7. Typical spectral format with a cross disperser and the short camera. Interorder separation is about 8 arcsec. The box shows the dimensions of a 4Kx4K CCD.

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Fig. 8. Matrix spot diagram. Boxx are 4x4 15 µm pixel wide. Wavelengths are measured in micron.

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