The ICE spectrograph for PEPSI at the LBT: preliminary optical design

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ABSTRACT

We present a preliminary design study for a high-resolution echelle spectrograph (ICE) to be used with the spectropolarimeter PEPSI under development at the LBT. In order to meet the scientific requirements and take full advantage of the peculiarities of the LBT (i.e. the binocular nature and the adaptive optics capabilities), we have designed a fiber-fed bench mounted instrument for both high resolution (R$\simeq$100,000; non-AO polarimetric and integral light modes) and ultra-high resolution (R$\simeq$300,000; AO integral light mode). In both cases, 4 spectra per order (two for each primary mirror) shall be accomodated in a 2-dimensional cross dispersed echelle format. In order to obtain a resolution-slit product of $\simeq$100,000 as required by the science case, we have considered two alternative designs, one with two R4 echelles in series and the other with a sigle R4 echelle and fiber slicing. A white-pupil design, VPH cross-dispersers and two cameras of different focal length for the AO and non-AO modes are adopted in both cases. It is concluded that the single-echelle fiber-slicer solution has to be preferred in terms of performances, complexity and cost. It can be implemented at the LBT in two phases, with the long-camera AO mode added in a second phase depending on the availability of funds and the time-scale for implementation of the AO system.

Keywords: Optical Instrumentation, High Resolution Spectrographs, Echelle Spectrographs, LBT

1. INTRODUCTION

The new 8–10m class telescopes have brought new opportunities for astrophysical research using high resolution (HR) spectroscopy. Over the last few years a number of HR spectrographs have been designed and manufactured for telescopes of this class[1,2,3,4,5]. Large telescopes allow us to extend high resolution spectroscopy to weaker sources, but a number of problems arise from the related larger beam diameters.

New spectrograph concepts, such as *white pupil* design, immersed gratings, active pupil correction and larger refractive or catadioptric cameras, have been developed. The performances of such spectrographs are always a compromise between spectral resolution, throughput, and spectral coverage. The main dispersing element adopted in all high resolution spectrographs studied or built so far is the *echelle* reflection grating. Resolution in Littrow configuration is given by the *resolution-slit product*:

$$R\varphi = 2(d/D)\tan\delta \tag{1}$$

where R is the resolution, φ is the angular slit width on the sky, d is the beam diameter at the collimator, D is the telescope diameter and δ is the blaze echelle angle.

Modern high resolution spectrographs for 8–10m class telescopes have a maximum resolution-slit product of $\simeq$40,000 arcsec[6]. Such a number comes from state-of-the-art technology in optical component manufacturing. The straightforward way to increase the *resolution-slit product*, for a telescope of a given aperture D, is to

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increase the blaze angle δ and/or the beam diameter d. R4 echelles, corresponding to $\delta = 76°$, 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 grooved area in currently available ruling engines, i.e. about 20 cm.

The other way to increase the resolution is to narrow the entrance slit of the spectrograph. A narrower slit however reduces the instrument throughput and requires an adequate sampling. For instance, an instrument with $R\varphi = 40,000$ 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 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 currently available spectrographs can be pushed up to about $R \simeq 120,000$ (160,000 for HDS at Subaru). The use of adaptive optics to increase the slit throughput is instead the object of recent studies[7,8,9] but has found so far only limited practical application in the optical.

In this paper we will present two alternative solutions to reach high-resolution HR (R$\simeq$100,000) and ultra-high resolution UHR (R$\simeq$300,000) at optical wavelengths for the specific case of the PEPSI spectropolarimeter at the LBT[10]. The PEPSI fiber-fed instrument requires that four spectra per order are recorded simultaneously in a two-dimensional cross-dispersed format. The requirement of four spectra per oder is dictated by the binocular nature of the LBT and the need to record simultaneously two different polarizations (either linear or circular) from the two LBT mirrors. Although the spectrograph can be used in integral light (i.e. with the two polarimeters removed from the beam), the contraint of four spectra per order, and hence of sufficient interorder spacing, remains also in this case. We have considered two solutions to reach a resolving power of $\simeq$100,000 as required by the scientific case. The first one is based on two R4 echelle gratings which allow us to double the currently achievable $R\varphi$ value, albeit at the expenses of reduced efficiency; the second one uses a fiber pupil slicer to reach an *effective* $R\varphi\simeq$100,000. In both cases adaptive optics is used to implement an ultra-high resolution (R$\simeq$300,000) mode.

2. SCIENTIFIC MOTIVATIONS FOR HR AND UHR SPECTROSCOPY

High resolution spectroscopy (i.e. resolving powers of R$\simeq$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 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 rotational velocities, convective motions, pulsations, mass losses, magnetic fields, and many others. HR spectrographs working at resolutions of 40,000–100,000 on 8–10m class telescopes (as well as on 4m and smaller telescopes for brighter objects) have already demonstrated the power of HR spectroscopy in many different research areas[11].

Stellar objects remain the most easily accessible targets, but narrow absorption lines in QSOs and distant galaxies have also become observable, at least for the brightest of these objects. These lines provide information about the chemical evolution of galaxies over cosmologically long timescales, the nature and kinematic structure of early galaxies and the distribution and kinematics of the intergalactic medium[12,13,14,15,16]. Pioneering work has been done on these systems at resolutions of $\simeq$50,000–100,000 with HIRES at Keck and UVES at the VLT, but a spectrograph with a resolution even higher is clearly needed to fully resolve the complex structure of the Lyman forest and other absorption features in QSO spectra.

HR and UHR is also crucial to resolve the velocity structure of interstellar medium (ISM) clouds in our Galaxy[17,18] as well as to determine the ^{6}Li/^{7}Li isotope ratio in the ISM, a fundamental parameter to investigate the production of Li by cosmic rays during galactic evolution. The thermal width of strong interstellar lines such as Na I and Ca II is very narrow in the cold ISM and requires resolutions $\geq$300,000 for all temperatures $\leq 10^4$ K to resolve the intrinsic line profile. This in turn is needed to measure directly the temperature of the diffuse clouds and the magnitude of any turbulent velocity field.

Abundance determinations in stars of different populations remain a key tool to study stellar evolution and the formation of the galactic disk, of the bulge and of the halo[19]. Although abundance determinations can be made in some cases using equivalent widths rather than line profiles, high resolution is required in many cases to

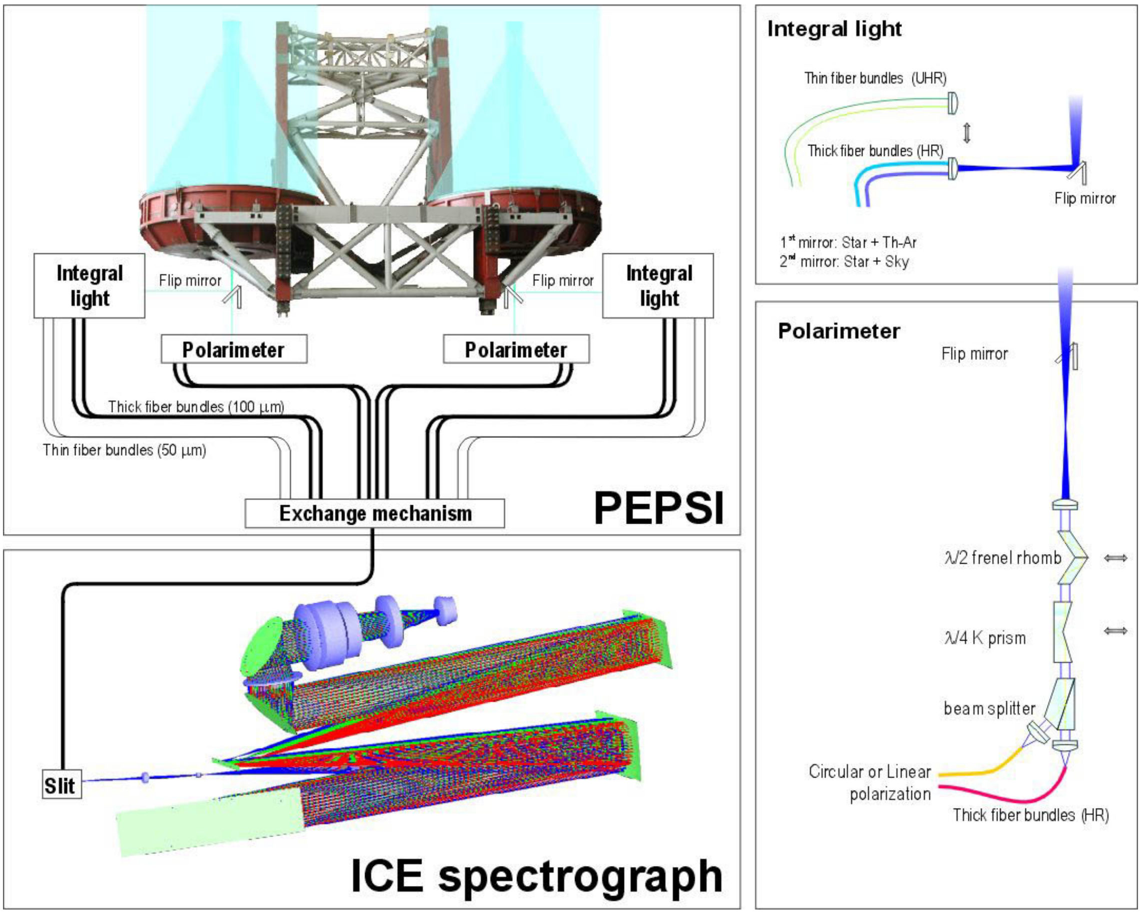

Figure 1. Schematic layout of the PEPSI spectropolarimeter.

resolve blends and for accurate matching of the observed line profiles to synthetic ones. 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 abundance in stars allow investigating stellar interior mixing processes as well as primordial nucleosynthesis and Li enrichment throughout the history of our Galaxy[20,21].

The determination of accurate line profiles in the spectra of stars allow studying velocity fields in stellar atmospheres[22,23,24]. Line profiles and line bisectors observed at very high resolution and S/N in late-type stars allow us to derive information on convective motions generated in subphotospheric convective zones. Asymmetries and shifts 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[25]).

Finally, the determination of precise radial velocity variations by means of HR spectroscopy allows us to search for exoplanets orbiting nearby stars, as well as to determine stellar pulsations and oscillations. The existence of planetary size bodies orbiting nearby stars has been clearly demonstrated on the basis of accurate radial velocity measurements[26,27], but much remains 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 required together with high throughput of the telescope-spectrograph combination. The large aperture of 8-10m class telescopes offers this possibility for the first time. A UHR spectrograph (R$\simeq$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, velocity fields in stellar atmospheres, and the study of the interstellar medium are all expected to greatly benefit from UHR 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[10]. The spectrograph we will discuss in the following sections offers these various capabilities, including a range of possible resolutions (from HR to UHR) as well polarimetric capabilities.

3. THE PEPSI SPECTRO-POLARIMETER FOR THE LBT

The possibility of implementing high-resolution spectroscopy at the LBT was first discussed by Pallavicini[28]. The binocular nature of the telescope and the emphasis that it puts on interferometry pose severe constraints for the design of a spectrograph for the LBT. Unless the same instrument is duplicated for both mirrors, any instrument at the LBT should either use the combined focus (coherently or incoherently) or should try to get complementary information from the two mirrors. Further constraints are imposed by the fact that most focal stations (including the direct F/15 Gregorian focii and the bent Gregorian focii) are either allocated to first generation facility instruments (MODS, LUCIFER, LBC) or are reserved for future interferometric modes[29]. On the other hand, the large collecting area of the LBT (two 8.4m telescopes rigidly mounted on the same mechanical structure) and the foreseen availability of AO at all focal stations due to the adaptive optics secondary make the LBT ideally suited for high-resolution spectroscopy.

Of the various spectroscopic instruments that can be envisaged for the LBT[28], two appear particularly attractive at optical wavelengths, taking into account the time frame in which the LBT will become operational, i.e. several years after the development of spectroscopic instruments at other 8-10m class telescopes. The first is a bench-mounted fiber-fed spectrograph which uses AO and reaches a very high-resolution (R>200,000). An instrument like this one would take advantage of the AO correction to narrow the spectrograph entrance slit to <0.2 arcsec while keeping the resolution × slit product (and hence the size of the beam) comparable to that of UVES (i.e. $R\varphi\simeq$40,000, beam size 20 cm). No spectrograph at present (except UHRF at the 4m AAT[30]) is able to reach such a high spectral resolution. Such an instrument requires a very stable location and could be accomodated in the telescope pillar by feeding it through fibers from the direct F/15 Gregorian focii by sharing that focal station with the multi-object low-resolution spectrograph MODS.

The other spectroscopic instrument that appeared to be attractive for the LBT is the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) proposed by the Astrophysical Institute of Potsdam[31]. It is again a fiber-fed bench-mounted cross-dispersed echelle spectrograph fed from the F/15 direct Gregorian focii. Although intended for use in the non AO-mode, it offers the novel feature of a polarimetric unit on each of the two telescopes for simultaneous observation of circularly and linearly polarized light. To this aim, two fibers per polarimeter are used to feed the spectrograph, and 4 spectra will be recorded simultaneously on a bidimentional detector (Figure 1). Such an 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. Alternatively, the spectrograph could also be used in the non-polarimetric mode using integral light. In this case, the four spectra per order could accomodate a sky fiber and a wavelength reference fiber (for accurate radial velocity measurements), in addition to two separate spectra of the target source, each obtained by one of the two telescope mirrors.

The two concepts above have been combined in one instrument (*PEPSI with ICE*) which is currently under development by the Astrophysical Institute of Potsdam (AIP) and by a Consortium of Italian Institutes

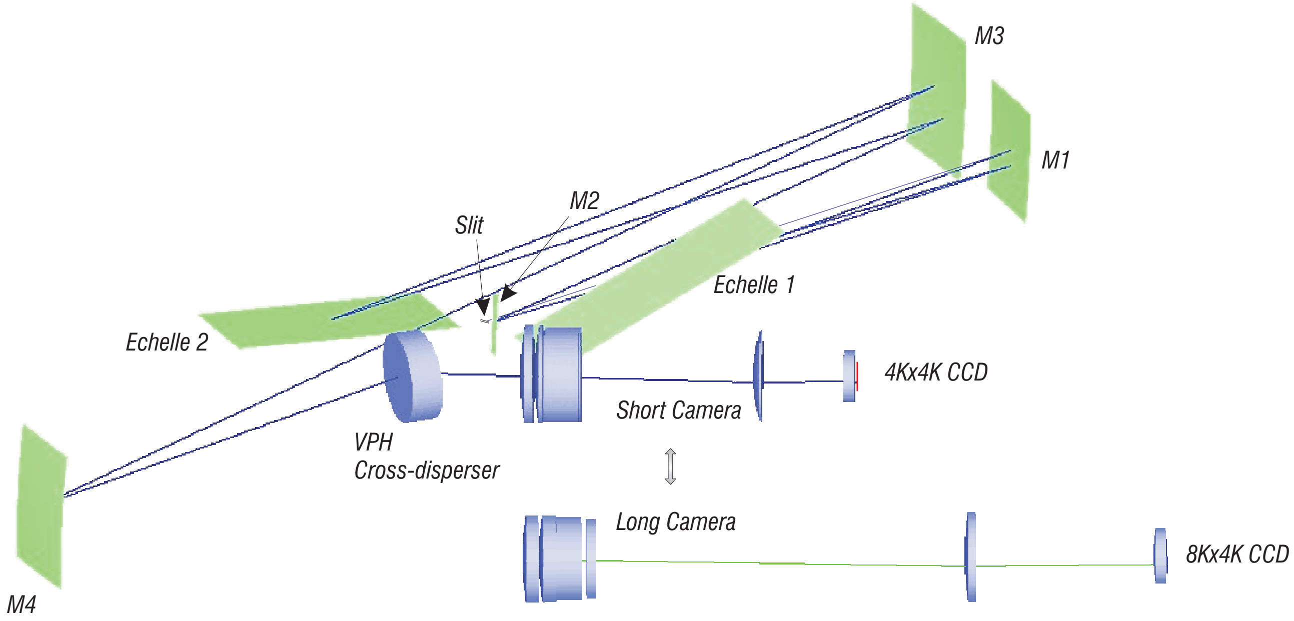

Figure 2. ICE double echelle 3D optical layout.

comprising the Astronomical Observatories of Brera, Palermo and Catania, all parts of the newly born Italian National Institute of Astrophysics (INAF). The science case for this instrument is illustrated in Strassmeier et al.[10] while the polarimeter (which is under the responsibility of AIP) is discussed in Hofmann & Strassmeier[32]. In the following we will focus on the ICE (Italian Consortium Echelle) Spectrograph a preliminary design of which, based on a double echelle solution, was presented by Zerbi et al.[33]. Besides summarizing that design, we will present here in more detail an alternative design based on a single echelle and a fiber slicer.

4. DOUBLE ECHELLE SOLUTION

A way to increase $R\varphi$ without increasing the size of the beam and/or the grating blaze angle is to use 2 echelle gratings mounted "in series", in order to increase angular dispersion. Such an idea was previously used in the MEGA monochromator[34]. MEGA, built for $R\simeq$2,000,000 using four echelles, was not conceived for astronomical use and hence was not optimized for efficiency. We combined this idea with the white-pupil design taking advantage of the optical quality given by such configuration. The white pupil design has been introduced by Baranne[35] and successfully adopted in many modern high resolution spectrographs like UVES[2] at the VLT, HRS[3] at HET, FEROS[36] at the ESO 1.5m (now at the MPG/ESO 2.2m) and SARG[37] at TNG. We briefly describe here this design and refer the reader to Zerbi et al.[33] for details.

A modified white pupil design (Figure 2) reforms a first white pupil on an R4 12.9 gr/mm echelle grating, a second time on a second identical R4 echelle, and a third time on the cross-disperser, reaching a *resolution-slit product* $R\varphi \approx 80,000$ with a beam size of 16 cm, i.e. similar to that of UVES (20 cm). To counterbalance the lower efficiency of the two echelle 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[38], which provide measured efficiencies up to 95%.

To feed the spectrograph two standard fiber core diameters have been selected, 200 μm and 50 μm, corresponding to 1 arcsec and 0.25 arcsec, respectively. The smaller fibers are intended to be used with AO correction for the UHR mode. A set of input and output microlenses match telescope (F/15) and spectrograph (F/10) focal ratios. When used in the HR mode with 1 arcsec fibers, minimum interorder separation must be about 8

Table 1. Total throughput for ICE in the double echelle configuration with the short camera.

λ (nm)	550	700	900	
Optics	0.79	0.79	0.79	beam size 160 mm
2 echelles	0.30	0.30	0.30	R4 12.9 gr/mm
Cross disperser	0.92	0.91	0.92	4 different VPH
CCD QE	0.92	0.87	0.51	4K×4K 15 μm
Telescope	0.75	0.75	0.75	2 mirrors
Fibers	0.80	0.80	0.80	200 μm fibers
Total	0.12	0.11	0.07	

arcsec. In the UHR mode, the same interorder separation is too small to use Bowen & Walraven image slicers, because these ISs put the slices one above the other along the slit direction. Adaptive Optics is the best solution in this case in order to obtain very high spectral resolution.

To match the different resolutions with adequate sampling, we have adopted two cameras, one for HR (R$\simeq$80,000) and the other for UHR (R$\simeq$320,000). The f/3.0 short camera and the f/4.9 long camera are both dioptric cameras, with no vignetting and an external focus. A 4Kx4K (mosaic) CCD is needed with the short camera, while a 8Kx4K mosaic is required by the the higher resolution long camera. It may be convenient to use only one 8Kx4K CCD mosaic with both cameras, using only one half of the CCD area with the short camera. In this case, a mechanical system is required to exchange cameras. The wavelength range from 500 to 1000 nm is covered in 150 orders. Each exposure covers from 30 to 45 echelle orders and 4 exposures are thus required to cover the full spectral range. Different VPHs, optimized for each wavelength range, are used for the four exposures.

Throughput has been evaluated under the following assumptions: a 1% efficiency loss at each air-glass interface and 2% efficiency loss at each (coated) mirror reflection. Echelle efficiency is estimated according to measured values obtained for the UVES echelle. The efficiency of the VPH gratings has been estimated with a Rigorous Coupled Wave Analysis (RCWA). For the CCD quantum efficiency we have used current Marconi data for deep-depleted red-optimized devices. Telescope transmission has been estimated from measured values of the VLT primary and secondary mirrors. Fiber efficiency is evaluated taking into account entrance and exit losses but not including slit losses which depend strongly on seeing. The calculations have been carried out at three wavelengths (550, 700 and 900 nm) and the results are given in Table 1.

In HR mode at R=80,000 the limiting magnitude in integral light is V=20.0 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/arcsec^2, seeing 0.7 arcsec). With the same assumptions and considering an AO system capable of concentrating 70% of the light into a 0.25 arcsec fiber, in UHR mode at R=320,000 the limiting magnitude is V=18.6.

5. SINGLE-ECHELLE FIBER-SLICER SOLUTION

The efficiency of the double-echelle configuration is significantly lower than that of a single echelle configuration. Moreover the adopted echelle pitch angle of 12.9 gr/mm (required to limit the FSR and hence the size of the detector) is not currently available and may impact heavily on the total cost. A double echelle configuration appears also more complex in terms of mechanical structure and alignement. An alternative ICE design relies on a more traditional white-pupil concept with a single R4 31.6 gr/mm echelle mosaic, a set of VPH gratings as cross dispersers and a fiber pupil-slicer, giving an *effective* resolution R$\simeq$100,000 with fiber size $\varphi\simeq$0.33”. In integral light mode, the spectrograph can have a UHR mode (R$\simeq$300,000) by concetrating the light in smaller fibers ($\varphi\simeq$0.13”) by means of adaptive optics and by using a second longer camera for proper sampling. Particular care has to be taken of the fiber feed system which will use input and output fiber microlenses and appropriate fore-optics and post-optics. A mosaics of two 2K×4.6K 13.5 μm CCDs arranged in two different

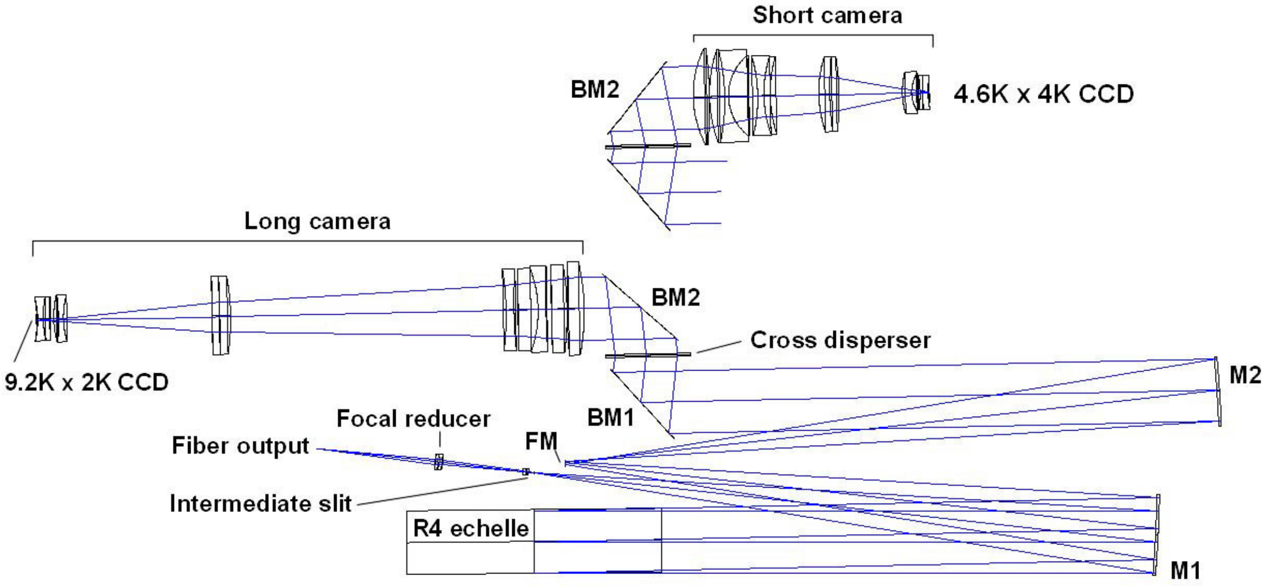

Figure 3. 2D ICE optical design in the single echelle configuration. After the cross disperser, a turnable mirror redirects the beam to the long camera or to the short camera. In the figure the short camera is shown shifted upward for clarity.

patterns are used for the two cameras in order to cover the wavelength range from 450 nm to 1100 nm in a limited number of exposures.

5.1. Optical layout

The optical layout of the single-echelle fiber-slicer solution is shown in Figures 3 and 4. At the end of the fiber bundles, a microlens array and a focal reducer reimages an intermediate slit at the spectrograph F/10 entrance. The HR and UHR modes use two different fiber core diameters (100 and 50 μm); then, two different microlens arrays and two different focal reducers must be used to match spectrograph entrance focal ratio.

A first parabolic off-axis mirror M1 acts as collimator, illuminating a R4 31.6 gr/mm 200×800 mm mosaic echelle grating used in Littrow configuration with a small 0.6° off-plane angle. After diffraction, the beam is refocused by M1 (used in double-pass) near the slit position, where a folding mirror FM reflects it back toward a second off-axis parabolic mirror M2, casting a white pupil onto the cross disperser. Different VPH cross dispersers can be exchanged to optimize efficiency and interorder separation, putting them on a wheel or a linear mechanism. BM1 and BM2 plane mirrors are mounted on turnable tables. Varying the BM1 angle, the VPH efficiency can be maximized, while BM2 allows switching between the two cameras. These two cameras have fixed positions and share the same optical axis. The short camera is optimized for the HR mode, the long camera for the UHR mode. Two different CCD mosaics are placed at the camera focii. In the short camera a mosaic CCD 4.6K×4K covers the whole spectrum in four exposures. The long camera is equipped with a 9.2K×2K mosaic, observing only few orders ($\simeq$7) per exposure. To recover the full spectral coverage a two-axis mechanism on BM2 is needed to select different orders.

5.2. Fiber feed system

Here we limit ourselves to the fibers for the HR mode. Our design has a resolution-slit product of $\simeq$40,000 arcsec at blaze peak. In order to obtain an effective resolution of $\simeq$100,000 we need a slit width of 0.33", that can be obtained by using an image slicer to reduce slit losses. The conventional solution (Bowen & Walraven

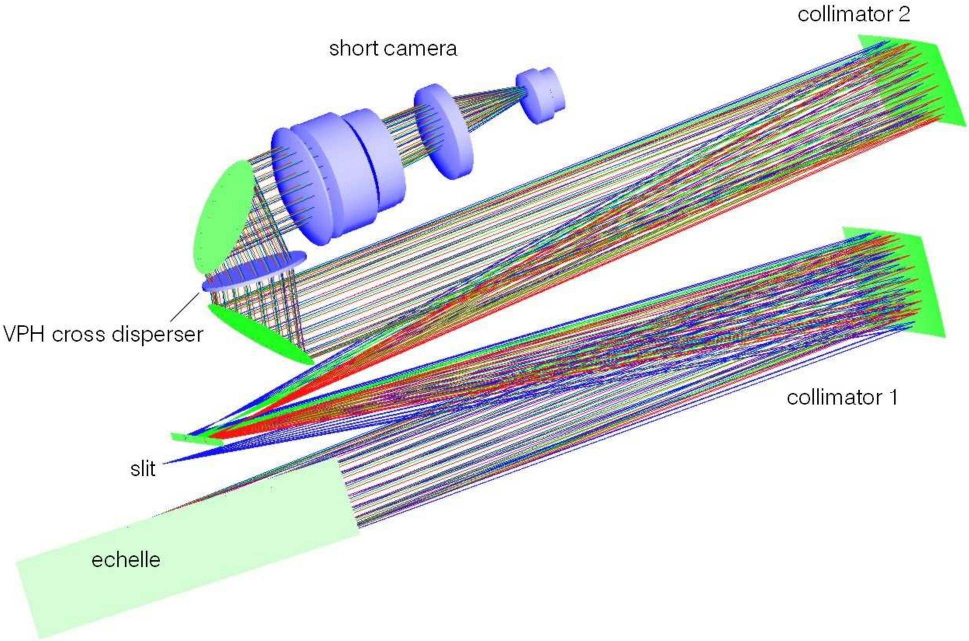

Figure 4. 3D ICE optical design with the short camera.

image slicer) requires a large number of slices one above the other along the slit. However the PEPSI design requires the simultaneous recording of four spectra per order, and thus it would require an interorder separation four times larger in order to use a conventional image slicer. A non-conventional solution is to use a fiber slicer that requires a lower interorder separation. To minimize slit losses a hexagonal microlens array feeds a bundle of seven fibers (Figure 5). Considering fiber focal ratio degradation (FRD), microlens dimensions, and other fiber constraints, we have selected 100 micron core diameter fibers as preliminary best choice.

Each microlens has a diameter of 500 μm, corresponding to a slit size of 0.33 arcsec. The required input focal ratio is F/37 *on the microlens surface*, that is converted into F/7 (in air) for the input fiber end. From Barden[39] we estimate a FRD $\approx$ 0.87. Between the telescope F/15 focus and the F/37 microlens array, a telecentric focal elongator is required. At the output of the fiber, a second microlens array (again with a diameter of 500 μm) reforms a pupil for each fiber output, simulating a narrower slit of 0,40×3,50 arcsec^2, thus implying a spectral resolution of 98,500. The output focal ratio is F/24 to be converted into F/10.5 with a focal reducer. This last focal ratio is higher than the collimator one to avoid echelle vignetting. The focal reducer consists of two doublets with a very high image quality to ensure no image degradation at the camera focal plane. Accurate positioning and alignment of the output microlenses are needed to ensure the maximum spectrograph throughput, the vertical alignment of the slit projection on the CCD and the best focus.

5.3. Cross dispersers

In order to maximize spectrograph throughput we have selected Volume-Phase Holographic (VPH) gratings as cross-dispersers. The PEPSI wavelength range from 450 to 1100 nm is covered in 81 orders. About 25 orders can be arranged on a CCD chip with a 4K height. At least four exposures are thus needed to observe the whole spectrum, allowing some wavelength overlap between different exposures. Each cross disperser is optimized to have a maximum efficiency in that range. Efficiencies greater than 90%. are possible.

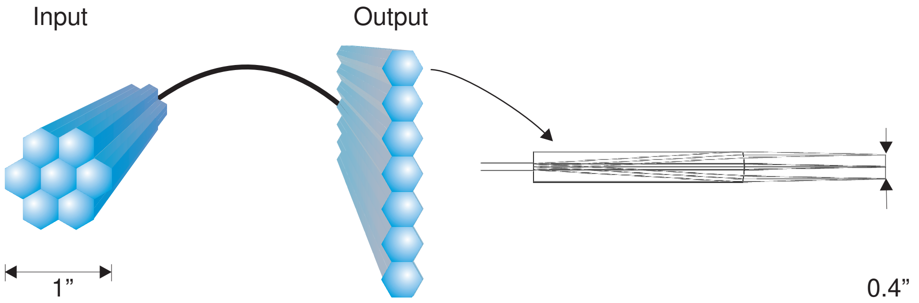

Figure 5. Fiber pupil slicer layout for the HR mode. The image in the focal plane is sliced by an input microlens array and is arranged at the output end in a linear array.

Table 2. Characteristics of the two ICE cameras.

	Short camera	Long camera
Focal ratio	2.27	3.64
Spectral range (nm)	420–1100	420–1100
Focal length (mm)	500	1202
Field (mm)	62×56	124×28

The same VPH cross dispersers can be used with the long camera, but now the interorder separation is smaller, due to adaptive optics. A second set of cross dispersers can be used if we want to cover a larger wavelength range per exposure.

5.4. Cameras, detectors and spectral formats

Two cameras are necessary to sample correctly the two fiber diameters: a short camera for the HR mode, and a long camera for the UHR mode. The short camera is an all-refractive camera made of 12 lenses in 6 groups. Its optical design has been optimized taking into account the spectrograph design. Its last surface is a cilindrical one to compensate field curvature introduced by the off-axis parabolic collimators. Also, the last doublet serves as dewar window. The long-camera performances are similar to those of the short-camera. The characterists of the two cameras are summarized in Table 2.

Our preliminary choice for the detector is Marconi CCD42-90 back illuminated deep depletion 2048 × 4608 13.5 μm pixel. A total of four CCDs are needed for ICE: two CCDs for the short camera, arranged in a 4.6K×4K mosaic, and the other two for the long camera, arranged in a 9.2K×2K mosaic.

With the short-camera full spectral coverage (FSRs shorter than CCD width) is obtained up to 910 nm with small losses at the borders for longer wavelengths. Minimum interorder separation is 18 arcsec. With the long-camera only a few orders per exposure can be observed due to the higher dispersion. However, at very high resolution we are usually interested only in observing small parts of the spectrum, so there is no need to ensure a simultaneous large spectral coverage. Tilting the second folding mirror BM2 we can select different orders. Full spectral coverage is reached up to 770 nm with small losses at longer wavelengths. Perhaps it is advisable to add a wedge to recover lost spectrum.

Spot diagrams for the short camera indicate a very high image quality. The image quality is high enough also for the long-camera, but perhaps there is space for some improvement. Table 3 summarizes image quality data and Figure 6 shows spot diagrams for selected wavelengths (for the blaze peak and the FSR borders) with the short camera. The image quality is better than in the double echelle configuration, assuring a spectral resolution within instrument requirements everywhere in the spectrum.

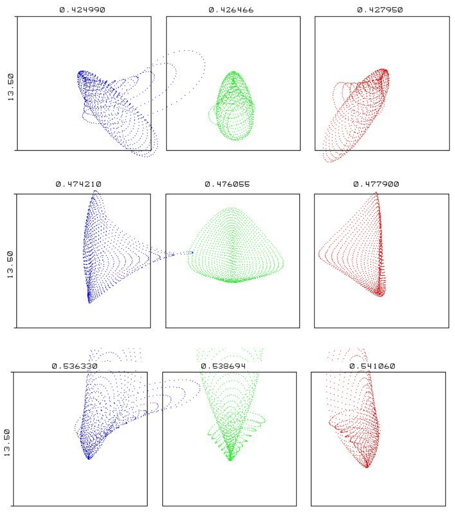

Figure 6. ICE spot diagrams with the short camera. Boxes represent one pixel size. Spots diagrams are shown for three wavelengths (426, 476 and 539 nm, rows) and for the center and borders of the FSR of the three orders (columns).

Table 3. Image quality data for ICE in the single echelle configuration.

	Short camera	Long camera
RMS spot diameter – typical (μm)	3–4	4–6
RMS spot diameter – maximum (μm)	7	9
Geometric diameter – maximum (μm)	17	18

5.5. Throughput and limiting magnitude

An estimate of total throughput has been made under the same assumptions used above for the double-echelle solution. These results are summarized in Table 4.

A comparison with the double echelle configuration (Table 1) shows that the efficiency of the single echelle configuration is at least a factor 2 higher than for the double-echelle case due to the different total efficiency of the echelle grating(s) in the two cases. From these values we have derived limiting magnitudes (including the effect of seeing and the two primary mirrors). At R=100,000 in 1 hr exposure at S/N = 10 per resolution element and with seeing of 0.7”, the limiting magnitude is V=20.4, about two magnitudes better than UVES at the same resolution.

Table 4. Total throughput of ICE in the single echelle configuration with the short camera.

λ (nm)	550	700	900	
Optics	0.77	0.77	0.77	beam size 200 mm
Echelle	0.71	0.69	0.68	R4 31.6 gr/mm
Cross-disperser	0.93	0.92	0.94	4 different VPH
CCD QE	0.92	0.87	0.51	4.6K×4K 13.5 μm
Telescope	0.75	0.75	0.75	2 mirrors
Fibers	0.80	0.80	0.80	100 μm fiber bundles
Total	0.28	0.26	0.15	

6. CONCLUSIONS

We have presented the preliminary design of a HR and UHR echelle spectrograph (ICE) to be used as part of the spectropolarimeter PEPSI under development at the LBT. The binocular nature of the telescope and the scientific requirements for polarimetry and ultra-high resolution dictated a fiber-fed bench-mounted spectrograph located far from any movable telescope parts, in a thermally controlled enviroment in the central pillar of the LBT structure. Two removable polarimeters share the two direct F/15 Gregorian focii of the LBT with the multi-object low-resolution spectrograph MODS. Light from the two polarimeters feeds the spectrograph via two fibers per polarimeter to allow the simultaneous recording of two different polarizations (either linear or circular). When the polarimeters are removed, the spectrograph is fed with integral light by a similar set of four bundles (one for the object from either mirror, one for the sky and one for a wavelength reference source). A different sets of fibers can be used in conjunction with the AO system of the LBT to implement an integral light UHR mode. In all cases, four spectra per order must be accomodated in a bidimensional cross-dispersed echelle format.

We have considered two alternative designs to obtain a resolution–slit product of about 100,000, twice as much as currently obtained in high-resolution spectrographs at 8-10m class telescopes. The first design assumes two R4 12.9 gr/mm echelle gratings mounted in series, while the second one assumes a single R4 31.6 gr/mm echelle grating and a fiber slicer. A white-pupil design, high-efficiency VPH gratings as cross dispersers and two different cameras for the HR non-AO mode and for the UHR AO mode are assumed in both cases.

As expected, the double echelle configuration is significantly less efficient (by at least a factor of 2) and of lower image quality than the single echelle fiber-slicer solution. It is also more complex mechanically and more expensive. On the contrary, the single echelle fiber-slicer solution has a very high efficiency and good image quality and promises to be an excellent choice for PEPSI. Estimates of the expected troughput based on realistic assumptions and average seeing conditions result in a limiting magnitude V=20.4 at R=100,000 in 1 hour at S/N=10 per resolution element, about two magnitude weaker than UVES at the same resolution.

The final design we propose for the ICE spectrograph for PEPSI is modular, with the HR and UHR modes requiring different cameras, different CCD mosaics and different fiber bundles, that could be implemented at different times. Since the UHR mode requires adaptive optics correction and is expected to be used only in integral light, it could be implemented at a later time depending on the availaibility of funds and on the time scale of the implementation of the AO system.

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