SixPak - a wide-field IFU for the William Herschel Telescope

Lars B. Venema*[a], Ton Schoenmaker[a], Marc Verheijen[c], Scott Trager[c], René Rutten[b], Matthew Bershady[d], Søren Larsen[e], Reynier Peletier[c], and Marco Spaans[c]
[a]ASTRON, Netherl. Foundation for Research in Astronomy, PO Box 2, 7900 AA Dwingeloo, NL;
[b]ING, Apartado de Correos 321, E-38700 Santa Cruz de la Palma, Canary Islands, Spain
[c]Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, NL
[d]University of Wisconsin, Dep. of Astronomy, 475 North Charter Street, Madison, WI 53706, USA
[e]Astronomical Institute, Utrecht University, Princetonplein 5, 3584 CC Utrecht, NL

ABSTRACT

We intend to construct SixPak, a wide-field fibre-based IFU for the 4.2-meter William Herschel Telescope on La Palma. The fibre bundle will consist of 238 fibres, each 3.0 arcsec in diameter, piping light from the Nasmyth focal plane of the WHT to the existing WYFFOS bench spectrograph. A total of 217 fibres will be densely packed to span a hexagonal field of view of 64 x 55 arcsec. The remaining 21 fibres will collect light from the sky background. SixPak is optimized for 2-dimensional spectroscopy at intermediate resolutions of extended objects of low surface brightness. At Nasmyth focus, a focal reducer matches the f-ratio of the telescope (f/11) to the "optimal" f-ratio of the fibres (f/3) to reduce the losses due to focal ratio degradation in the fibres. Microlenses convert the output f-ratio of the fibres to the f-ratio of the WYFFOS collimator (f/8.2). By means of an exchangeable slit at the pupils of the microlenses, a spectral resolution of R = 10,000 can be achieved. The intention is that SixPak will be open for general use in order to allow easy access to the broadest possible astronomical community.

Keywords: Fibre fed integral field spectrometer, WHT, WYFFOS

1. INTRODUCTION

SixPak is an integral wide field fibre unit between the 4.2m William Herschel Telescope (WHT) on La Palma and its spectrometer WYFFOS. The fibre-bundle will span a hexagonal field-of-view, 1 arcminute in diameter, piping light through 238 fibres from the Nasmyth focal plane of the WHT to the existing WYFFOS bench spectrograph. It will allow for 2-dimensional wavelength-agile spectroscopy at intermediate resolutions (R=10,000) of extended objects of low surface brightness, thus enabling a plethora of scientific investigations that closely match several areas of astrophysical research in The Netherlands. In particular, SixPak will be used to study the stellar kinematics in the faint outskirts of spiral and elliptical galaxies, to study spatially resolved stellar populations and abundances, to perform crowded-field spectroscopy of dense star clusters and clusters of galaxies, and to investigate the interstellar medium in the Milky Way and external galaxies. The design of SixPak is strongly based on earlier experience with SparsePak on the WIYN telescope's Bench Spectrograph (Bershady et al 2004a; 2004b) and P-PAK on the PMAS spectrograph on the 3.5m telescope on Calar Alto (Verheijen et al 2004; Kelz et al 2005). SixPak will be commissioned as a common user instrument to allow easy access to the broadest possible astronomical community.

This paper first discusses the science drivers behind this instrument and subsequently discusses the instrument concept. The paper concludes with some the performance estimates and a comparison with P-PAK on the Calar Alto telescope.

2. SCIENCE CASE

2.1 The Disk-Mass Project: dark and luminous matter in spiral galaxies

Scientific motivation

A major roadblock in testing galaxy formation models is the disk-halo degeneracy; density profiles of dark matter haloes as inferred from oft-used rotation curve decompositions depend critically on the adopted M/L of the disk component. An often used refuge to circumvent this degeneracy is the adoption of the maximum-disk hypothesis (van Albada & Sancisi 1986). However, this hypothesis remains unproven. Bell & de Jong (2001) have shown that stellar population synthesis

Ground-based and Airborne Instrumentation for Astronomy II, edited by Ian S. McLean, Mark M. Casali,
Proc. of SPIE Vol. 7014, 70140L, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.789130

models yield plausible relative measurements of stellar M/L in old disks, but uncertainties in the IMF prevent an absolute measurement of total disk M/L from photometry. At present, there are no techniques based on stellar populations or scaling relations that can provide absolute M/L ratios of stellar disks.

Measuring values of σ_z down to 10 km/s in the outer parts of galaxy disks – necessary to infer stellar M/L ratios -- requires spectroscopy with a spectral FWHM resolution of $R \approx 10^4$ on objects with a surface brightness as low as $\mu(B)=24.5$ mag/arcsec^2, the typical value at three disk scale-lengths from the centre of a normal spiral galaxy. With conventional long-slit spectrographs, this can only be achieved with exceedingly long integration times of several nights per object. The particular power of IFUs with nearly face-on galaxies lies in the ability to azimuthally average many fibres. This yields clean σ_z measurements well beyond 2 disk scale-lengths where contamination from bulge stars is negligible and the rotation curve of the stellar disk has reached its flat part.

We would like to augment the Disk-Mass Project by: a) including galaxies of low surface brightness, b) measuring σ_z through the CaII absorption lines and c) studying in detail the vertical structure and kinematics of edge-on galaxies. This requires an instrumental performance not provided by the SparsePak and P-Pak IFUs (see below). Our design for SixPak combines all positive aspects of SparsePak and P-Pak and will enable us to engage in these investigations.

The gravitational potentials of low surface brightness (LSB) galaxies are presumed to be dominated by dark matter at all radii. To spectroscopically resolve the stellar velocity dispersion in the kinematically cold disks of LSB galaxies, a spectral resolution of R=10,000 is required. Unfortunately, the maximum spectral resolution provided by the PMAS spectrograph into which the P-Pak fibres are fed is R=7,500, while the efficiency of the WIYN Bench Spectrograph (WIYN-BS) is too low to provide sufficient signal-to-noise at R=10,000 for galaxies at lower surface brightness levels. By combining a spectral resolution as provided by SparsePak with an efficiency as provided by P-Pak/PMAS, SixPak/WYFFOS on the 4.2m WHT will enable us to measure σ_z in the kinematically cold disks of LSB galaxies. This will allow us to establish the relative contributions of luminous and dark matter in LSB galaxies and to verify the presumed dominance of dark matter in these systems.

2.2 Stellar populations of galaxies

Stellar population analysis of the integrated spectra of distant galaxies is a powerful tool for understanding the formation and evolution of galaxies, as it allows us to probe their star formation and nucleosynthetic histories in detail (see Renzini 2006 for a recent review). With the completion of the SAURON Survey (Bacon et al. 2001; de Zeeuw et al. 2002; and many others), it is clear that the combined analysis of stellar population and stellar dynamics represents an even more powerful tool. Unfortunately, SAURON is limited to studying only massive galaxies in the very local Universe - out only as far as the Virgo Cluster at 17 Mpc - due to its low spectral resolution and limited spectral coverage respectively. A wavelength-agile, high-spectral-resolution integral-field spectrograph like SixPak coupled with WYFFOS eliminates both of these problems, and a wider field-of-view allows for a wider range of science projects. In particular, SixPak opens up a new regime of the parameter space of galaxy properties to integral field spectroscopy: galaxies in rich clusters of galaxies, the densest regions of the Universe.

The Coma cluster of galaxies

The nearest rich cluster to the Milky Way, the Coma Cluster, lies well beyond the reach of SAURON but its galaxies are easily accessible to SixPak. The largest galaxies in the Coma Cluster have half-light radii of about an arcminute, well-matched to SixPak's field of view. The massive galaxies in the Coma Cluster make excellent targets with SixPak to extend the study of the connection between kinematics and stellar populations of early-type galaxies pioneered by the SAURON survey to greater distances and to the densest environments. The high density of galaxies in the Coma Cluster also means that many dwarf galaxies can be observed in single pointings, making detailed studies of stellar populations and kinematics of the dwarf galaxies, especially those selected from the HST/ACS Coma Legacy Survey (of which Peletier is a team member), straightforward.

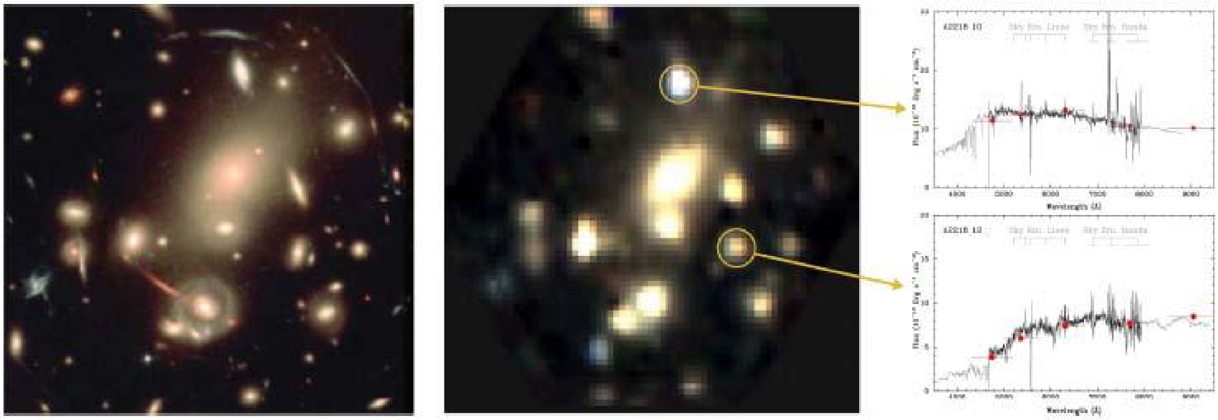

Figure 1: The rich cluster of galaxies Abell 2218 at z=0.2 observed by the Advanced Camera for Surveys on the Hubble Space Telescope (left) and the P-Pak/PMAS IFU (middle) at low spectral resolution. Note that even the faint gravitational-lens arcs are detected in the P-Pak composite "image" (e.g., the lower red arc). The right panels show two representative spectra from the P-Pak data cube: a foreground star-forming blue galaxy (top) and a red, old cluster member with clear strong G-band and MgH-band absorption (bottom). From Sánchez et al. (2007).

Distant galaxy clusters

Further afield, a key project of SixPak is to survey the stellar populations of cluster galaxies at a redshifts up to z ~ 0:5. Sánchez et al. (2007) made a first attempt at such a survey, observing the spectacular lensing cluster Abell 2218 using the P-Pak IFU mode of the PMAS spectrograph at Calar Alto (Figure 1). They were able to measure accurate absorption line strengths of more than a dozen galaxies and inferred stellar population parameters of nearly 30 galaxies in a single IFU pointing in only six hours of total exposure time. As a comparison, Barr et al. (2005) required 4-9 hours of exposure with the long-slit mode of the GMOS on the Gemini North 8.2-meter telescope to determine line strengths and stellar populations of 30 galaxies in a cluster at z = 0.28. Because the core radii of clusters at z ~ 0.2-0.5 are well-matched to SixPak's field of view, a large survey of cluster galaxy stellar populations at these redshifts can be undertaken in a reasonable amount of observing time (roughly one night per cluster), competitive with the largest ground-based telescopes.

2.3 The interstellar medium of the Milky Way and other galaxies

The broad wavelength coverage of WYFFOS (3700-7100 Å) allows one to probe a large number of ISM diagnostic lines in one sweep, e.g., [NII]5755, 6548, 6583 Å; [OIII]4363, 4959, 5007 Å; [OII]3729, 3726 Å; [SII]6716, 6731 Å; as well as lines of HI (Hα,Hβ), HeI, HeII, [NeIII], [NeIV], [MgI], and [ArV]. These lines allow one to determine, among others, the electron temperature, gas density and elemental abundances of the warm ionized gas. The fact one can spectrally cover spatially extended gas with SixPak/WYFFOS so well is crucial here since it helps one to assess spatial variations in the physical conditions of the gas. When combined with far-infrared measurements of atomic and molecular lines and dust continuum this allows one to constrain the feedback effects that stars (radiation sources in general) have on the ambient ISM (Meijerink et al. 2007).

Studies of local HII regions like the Orion Nebula allow us to study star formation, ionization processes, and the production of chemical elements in detail. Such studies are by their nature best performed spectroscopically or with narrow-band filters. However, in the optical, spectral studies of large, nearby HII regions have been hampered by the limited slit lengths and narrow slits of long-slit spectrographs or by the limited wavelength coverage of Fabry-Perot imaging spectrographs, while narrow-band studies have been limited to a few choice lines. Wide-field, wavelength-agile integral field units like SixPak coupled with WYFFOS overcome both of these limitations.

2.4 Other scientific projects

Apart from the abovementioned studies in which the authors of this proposal have a direct and keen interest, several other research areas would greatly benefit from the proposed SixPak IFU:

- Abundances in the outer regions of nearby galaxies
- The ISM in external galaxies
- Crowded-field spectroscopy of star clusters and star-forming regions
- Dark matter in early-type galaxies
- Surveys for high-redshift Lyα emitters

3. OPTIMIZED SOLUTION FOR THE EXISTING WYFFOS SPECTROGRAPH

3.1 SparsePak & P-Pak: wide-field IFUs and their limitations

For most of the projects discussed here, we require optical spectroscopy of extended low surface brightness objects at moderately high spectral resolution (R≈10,000). Consequently, many photons must be collected per spectrum in order to obtain enough signal to beat the read-noise of the CCD detectors. To achieve the required signal-to-noise, Bershady and Verheijen have built and commissioned two special purpose, fibre-based, wide-field IFUs.

SparsePak, a fibre-based IFU feeding the Bench Spectrograph at the WIYN 3.5m telescope, was constructed by Bershady at the University of Wisconsin in early 2001 (Bershady et al 2004a; 2004b). The light collecting power of each SparsePak fibre (4.7" in diameter) is truly unique and exceeds that of any spatial IFU element available on 8m-class telescopes. Obviously, the price to pay for a large collecting area per fibre is a reduced spatial resolution which is, however, of secondary importance for many projects. Unfortunately, the efficiency of the Bench Spectrograph is quite low (~6%) which has limited SparsePak observations to the brightest galaxies.

Given the relatively low efficiency of the WIYN Bench Spectrograph, a second special-purpose IFU, named P-Pak, was built by Verheijen at the AIP in Potsdam in late 2003 (Verheijen et al 2004; Kelz et al 2005). This IFU is now commissioned as a permanently installed module for the PMAS spectrograph on the 3.5m telescope on Calar Alto. Unfortunately, the best achievable spectral resolution with P-Pak is R≈7,500 which is not quite sufficient to spectroscopically resolve the stellar kinematics in low surface brightness galaxies for which R=10,000 is required. Furthermore, PMAS is mounted at the Cassegrain focus and its significant flexure limits the efficiency with which P-Pak observations can be performed. In addition, weather conditions at Calar Alto have resulted in an unlucky 40% success rate for observing runs with P-Pak.

To overcome the limitations of the SparsePak and P-Pak IFU's in spectral resolution, throughput, flexure, weather conditions and accessibility, we propose to build on our experience and develop SixPak, a wide-field IFU to be commissioned on the WHT, aiming to combine and supersede all the positive aspects of SparsePak and P-Pak. The performance, accessibility and spectral agility of the WYFFOS spectrograph, as well as its interchangeable slit assembly, makes WYFFOS the perfect `backend' for a new fibre-module.

3.2 SixPak specifications

The requirements of SixPak can be inferred from the previous discussion and are collected in Table 1. The WYFFOS spectrometer of the WHT was considered to be ideal to equip with SixPak, as its highest spectral resolution, the high throughput and the optical stability promised to solve the critical issues connected with the other systems.

Table 1. SixPak requirements

Requirements	
FOV	Effective diameter >1 arcmin Goal 3 arcmin (TBD)
Sampling density	No real spatial resolution requirement, at least 150 fibres
Grasp	3-4 arcsec per fibre
Wavelength range	$370 < \lambda < 700$ nm
Spectral resolution	I: $R \geq 10{,}000$ in range $490 < \lambda < 530$ nm II: full wavelength range in one or two exposures
Efficiency	Efficiency @ R~10,000 equal or better than P-PAK + PMAS

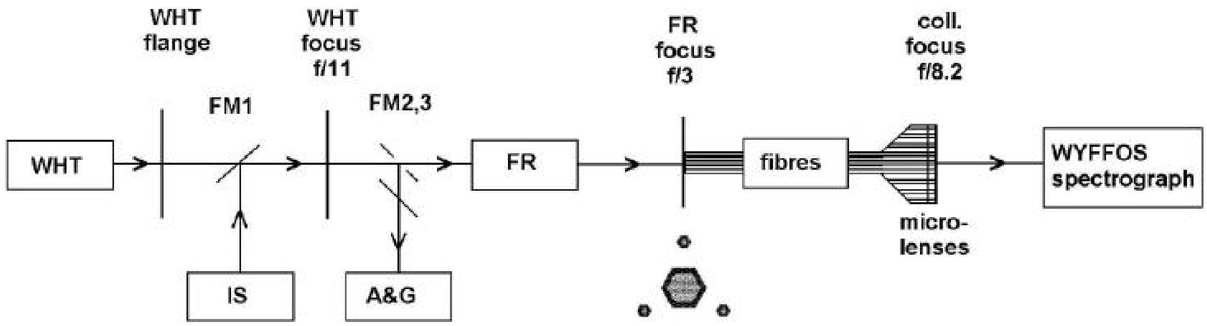

Figure 2: Schematic layout of SixPak. A retractable fold mirror (FM1) couples the calibration source into the optical path. The next folding mirror (FM2) consists of a flat mirror with a hole that transmits the inner 2.5 arcminutes of the field-of-view and reflects the outer 7 arcminutes to the acquisition and guiding system. A focal reducer (FR) couples the light into the fibre bundles.

3.3 Technical description of SixPak

Figure 2 shows the schematic layout of SixPak which is strongly driven by the experience with the P-Pak and SparsePak IFUs and by the characteristics of the WYFFOS spectrograph and the William Herschel telescope. A fibre-bundle picks off the light from a Nasmyth focal plane of the WHT telescope and transports it to the slit area of WYFFOS. The hexagonal IFU field is reordered into a long slit for the spectrograph, freeing one dimension of the detector for the dispersion of the light. Surrounding the IFU that picks up the science target, three small fibre-bundles record the sky background.

For the pickup location, the prime focus of the WHT has been considered. However, this focus was rejected by its complex and invasive mounting and the vulnerability of the long fibre bundle from the prime focus to the WYFFOS spectrometer bench. The spectroscopic and photometric stability will be less certain when the spectrometer is fed from the prime focus. One of the consequences of this focal station is the need of a focal reducer to adopt the scale of the IFU on sky,

The existing WYFFOS spectrograph has an f/8.2 collimator/camera arm in double pass (near-Littrow) with a reflection grating to form an intermediate spectrum close to a concave spherical relay mirror. In general a grating can be used with the grating normal pointing in the direction of the camera or pointing in the direction of the collimator. The first setting is to be preferred as both wavelength range and spectral resolution are larger and for further discussion it is assumed the grating is used in this setting. The spectrum is imaged onto a 2-chip EEV mosaic detector (4300 x 4200 pixels of 13.5 μm) by a Schmidt-type f/2.7 camera with a focal length of 293 mm. The total magnification (including collimator, grating, relay mirror and Schmidt camera included) is 0.338 in the field direction. The 57mm width of the detector corresponds to a curved entrance slit of 168 mm (radius of curvature is 1190mm). The pupil on the grating has a diameter of 115 x 194 mm.

Several ISIS gratings are available for WYFFOS. The low resolution requirements from the SixPak science case are not critical. Considering the required spectral resolution of 10,000, the currently available echelle with a ruling of 632 lines/mm (Milton Roy) and blaze angle of 57^o is most suitable. For a setting at a wavelength of 515nm in 5th order the scale factor at the detector is 0.720nm/mm (grating normal to camera). For the 2-chip EEV mosaic (4300 x 4200 pixels of 13.5μm) this means a wavelength coverage from 494 to 531nm for one setting. The FWHM of the blaze θ pattern may be approximated by $\theta = 180 \bullet \lambda / (\pi \bullet A \bullet \cos\gamma)$ degrees, where λ is wavelength (0.515 μm), A is grating constant (1.58 μm) and γ is blaze angle (57^o). Applying the numbers gives θ of 34.2^o. To centre 515 nm at the detector, the echelle has to be rotated over 2.39^o to 54.61^o. So this wavelength is well within blaze. The spectral resolution of R=10,000 limits the height of the exit pupils of the fibres in the pseudo-slit to 240μm.

Fibre based IFUs exhibit two major disadvantages that should be carefully taken into account:

1. The efficiency of transmission of fibres depends strongly on the focal ratio of the incoming and outgoing beam. The focal ratios of the outgoing beams tend to move towards the region f/3-5. Therefore entering with a slower

beam results in focal ratio degradation (FRD). The output focal ratio is always quite fast and the spectrometer should accept this or light is lost.

2. The filling factor of the focal area is always smaller than 1 because circular fibre cores are surrounded by their cladding and protective buffer. An optimization of the core versus overall fibre diameter is needed to maximize the efficiency.

At the telescope focus, both reducing the FRD and maximizing the grasp of a fibre implies a large plate-scale (arcsec/mm) in the focal plane which can be achieved by feeding the fibres with a fast (f/3) telecentric entrance beam. This necessitates focal reduction of the incoming F/10.96 beam at the Nasmyth port through a focal reducer. The f/3 beam was selected to be optimal as the light coupling efficiency into the fibre is high and the losses due to FRD are minimal, combined with an optimal plate scale.

Consequently, the light emerges from the fibres in the slit area at f/3 due to a limited Focal Ratio Degradation (FRD) at these fast acceptance angles. Matching the emerging f/3 beam to the f/8.2 of the collimator requires a focal expansion by means of micro-lenses (Figure 4, right). These micro-lenses magnify the fibre faces by a factor 8.2/3.0=2.73, and consequently, the physical core diameters of the fibres should be limited to 240/2.73=90µm. This core diameter was considered to be too small. Realizing that the exit pupil is circular instead of a slit, we decided to mask the exit pupil of the fibres with a 240µm slit cutting only in part of the light cone (illustrated in figure 3). To minimize cross-talk between adjacent spectra on the detector, the exit pupils in the pseudo-slit have to be sufficiently separated to allow for at least 4 dark pixels between the spectra, corresponding to a 200µm spacing between the exit pupils (see figure 3).

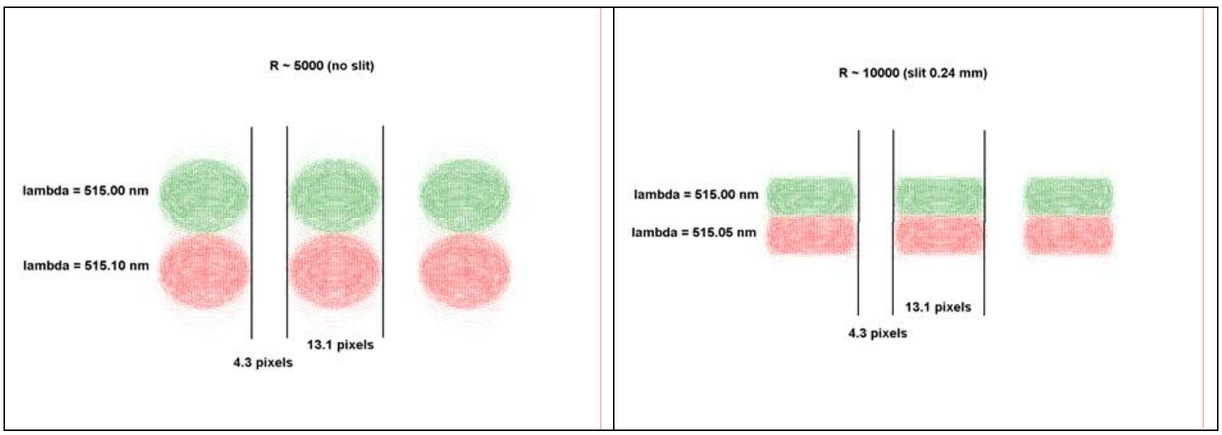

Figure 3: Simulation of spectral images in the centre of the detector to show spatial and spectral resolution for the final configuration. The separation between the spectra is 4.3 pixels, the spectra are 13.3 pixels wide. The left panel shows the separation of images for a spectral resolution of R ~ 5000 and no slit in the exit pupil of the microlens (diameter 500 µm); in the right panel the resolution is R ~ 10000 with a slit of 0.24 mm running over the exit pupils.

Having defined the interface requirements both at the telescope focus and in the pseudo slit of WYFFOS, we can construct a trade-off table for the various options for the IFU (table 2). The slit was completely filled with fibres. Larger fibre diameters yield a larger FOV, but maintaining the R=10,000 results in greater slit losses. The light loss remains limited (<40%) as long as the circular exit pupil does not exceed 500µm, resulting in a physical core diameter of the fibre of ~180µm. Consequently, a maximum of 238 fibres/micro-lenses can be placed along the 168mm length of the slit. Of these 238 fibres, 217 can be bundled in a tightly packed hexagonal grid to sample the focal plane. With an outer cladding diameter of the fibres of 225 µm, this hexagonal grid provides a field-of-view of 63×54 arcseconds with a filling factor of 0.58 (Figure 4, middle). The remaining 21 fibres will be grouped in 3 separate but fixed mini-IFU's to collect light from the sky background.

Table 2. Calculated characteristics for different sizes of hexagonal fibre bundles. For all calculations the fibre outside diameter is assumed to be 25% larger than the core diameter. The chosen configuration is highlighted.

science fibres	sky fibres	central row fibres	diameter exit pupil (mm)	diameter core fibre (mm)	spaxel size (arcsec)	Spectral resolution (no slit)	slit losses (%) for R=10000 (slit=0.24 mm)	field (arcsec)
169	21	15	0.678	0.250	4.08	3600	56	76 x 66
217	21	17	0.500	0.185	3.01	4800	41	64 x 55
271	21	19	0.369	0.122	2.22	6500	23	53 x 46
331	21	21	0.271	0.100	1.63	8900	5	43 x 37

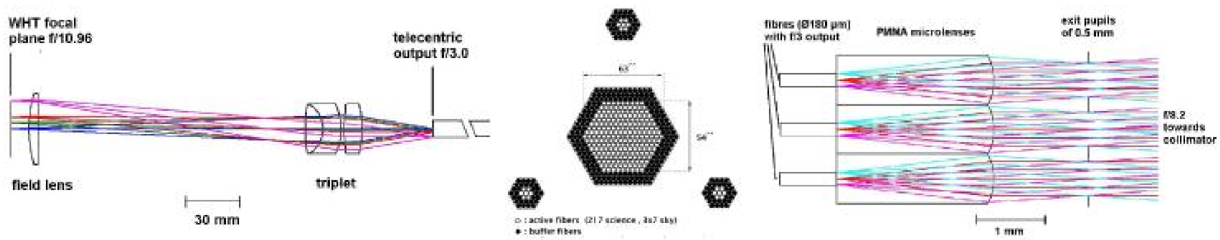

Figure 4: The optical layout of the focal reducer, consisting of four lenses of "standard" glasses. The right panel shows the fibre layout in the telescope focal plane (after focal reducer). The dark fibres are buffer fibres to ensure high quality scientific fibres in the block.

Figure 4 (left) shows the optical design of the focal reducer with a magnification of 0.27 (from F/10.94 to F/3.0). The field lens near the WHT focus re-images the pupil near the focus of the triplet, so the output beam of the triplet is telecentric. For the full wavelength range of 400-800 nm, the spot sizes vary slightly over the field-of-view (2.6' diameter), remaining within 0.8 arcsec for the science fibres (up to 30" from the field centre) up to 1.1 arcsec for the sky fibres at 80" from the field centre. Figure 4 (right panel) also shows the optical scheme for the micro-lenses. Each fibre is pressed onto a micro-lens made of PMMA (Polymethylmethacrylat) with one convex surface (R=0.769 mm). This material has >95% transmission (AR-coated) from 350 to 1200 nm and is often used by manufacturers of micro-lenses. To avoid losses at the end of the slit, the fibres and micro-lenses will be mounted on a surface with a radius of 1190 mm.

Table 3. Estimated optical throughput of complete optical system

optical element	number	per surface	transmission
WHT mirrors	3 surfaces	0.88	0.68
focal reducer	6 surfaces (AR)	0.985	0.91
fibre	2 surfaces + FRD		0.80
microlens	2 surfaces (AR)	0.985	0.97
spectral resolution			5000 / 10000
slit efficiency			1.00 / 0.59
collimator 2x	8 surfaces (AR)	0.985	0.89
echelle efficiency			0.70
order sorting filter			0.85
camera optics mirrors	3 surfaces	0.96	0.88
camera optics lenses	4 surfaces (AR)	0.985	0.94
camera vignetting			0.72
detector window	2 surfaces (not coated?)	0.96	0.92
detector efficiency			0.80
total throughput			0.111 / 0.065

To ensure a proper and expedient acquisition of the science targets and their subsequent centering onto the SixPak IFU, a robust Acquisition and Guiding (A&G) unit is a prerequisite for reliable and efficient observations with SixPak. It is foreseen that the A&G camera will sample a 7×7 arcminute field-of-view surrounding the circular science beam (2.6 arcminute diameter). A final design for the A&G unit still needs to be worked out in close collaboration with the ING technical staff. Furthermore, a calibration unit is required to wavelength-calibrate the spectra and to monitor the fibre performance. The calibration unit should consist of an integrating sphere with several calibration lamps and some relay optics to insert the calibration light into the image plane.

3.4 Efficiency estimate of SixPak

The estimated throughput of the complete optical system, including telescope, focal reducer, fibre, microlens and WYFFOS spectrograph, is given in Table 3. The estimated total throughput of 11% for R = 5000 compares favourably to the 6% of SparsePak. For the high resolution mode, the slit cuts out additional light reducing the throughput by a factor of 0.6.

Table 4. Comparison performance of PPAK and SixPak

instrument	PPAK	SixPak
observatory	Calar Alto	La Palma
telescope	CAHA-3.5m	WHT
diameter (m)	3.5	4.2
focal station	Cassegrain	Nasmyth
number of telescope mirror reflections	2	3
effective collecting area (m^2)	8.153	12.705
f-ratio telescope	f/3.3	f/3.0
collimator f-ratio	f/3.0	f/8.2
collimator focal length (mm)	450	820
camera f-ratio	f/1.5	f/2.7
camera focal length (mm)	270	293
slit length (mm)	96	168
detector	SITe ST002A	2-chip EEV
dimensions	2k x 4k	4300 x 4200
pixel size (microns)	15.0	13.5
gain (e^-/ADU)	1.4	0.88
read noise	5.0	4.4
QE 515 nm / 860 nm	0.76 / 0.64	0.82 / 0.34
number of fibres (science + sky + cal)	331 + 36 + 15	217 + 21
fibre core diameter (microns)	150	180
filling factor	0.60	0.58
spaxel size (arcsec)	2.7	3.0
specific grasp (m^2 x $arcsec^2$)	46.7	89.8
total science grasp (m^2 x $arcsec^2$)	15451	19489
diameter field of view (arcsec)	74 x 65	62 x 55
grating	J2100	632 l/mm echelle
order	2	5
dispersion (nm/mm)	1.44	0.72
dispersion (nm/pixel)	0.0216	0.0097
spectral range on detector (nm)	40	39
binning (spectral x spatial)	1 x 2	3 x 3
width of exit pupil (microns)	150	500 / 240
shape of exit pupil	circular	circular / rectangular
spectral resolution	7500	5000 / 10000
geom. loss by grating overfill)	15%	0%
geom. loss by camera obstruction	0%	28%
geom. loss by slit mask	0%	0% / 41%
normalized S/N	1.00	2.31 / 1.36

Table 4 makes a direct comparison between SixPak and PPAK. These numbers demonstrate that there is significant benefit building SixPak on the WHT and WYFFOS. On the other hand, the table also shows clearly where we lose efficiency compared to other systems. We can point to three main issues:

1. QE detector, the current chips used in WYFFOS loses significant QE in the red, so an upgrade in the detector will help considerably.
2. Geometric loss of slit mask. In essence, the current collimator of WYFFOS poses severe constraints on the fibre feed. This results in fewer fibres in the bundle and a loss of efficiency (0.6).
3. The WYFFOS camera has a central obscuration leading to 28% efficiency loss.

4. CONCLUSION

The current description of SixPak shows that extending WYFFOS with the newly designed fibre feed will provide La Palma with a very competing instrument for performing medium resolution spectroscopy on faint extended objects, particularly suitable for the faint outer regions of galaxies. This new instrument benefits from the spectral capabilities of WYFFOS combined with the actually ideal size of the WHT and the quality of the site.

Nevertheless, the study exposed also the weakness of the current configurations, where a dedicated design of the spectrograph could boost the sensitivity even more. Currently, we are looking into this option to see whether the gain in sensitivity justifies the additional costs for an improved spectrometer.

REFERENCES

[1] Bacon R., Copin Y., Monnet G., Miller B. W., Allington Smith J. R., Bureau M., Carollo C. M., Davies R. L., Emsellem E., Kuntschner H., Peletier R. F., Verolme E. K. & de Zeeuw P. T., (2001). MNRAS, 326, 23

[2] Barr J., Davies R., Jørgensen I., Bergmann M. & Crampton D. (2005), AJ, 130, 445

[3] Bell E.F. & de Jong R.S. (2001), ApJ, 550, 212

[4] Bershady M.A., Andersen D.R., Harker J., Ramsey L.W. & Verheijen M.A.W. (2004a), PASP, 116, 565

[5] Bershady M.A., Andersen D.R., Verheijen M.A.W., Westfall K.B., Crawford S. & Swaters R.A. (2004b), ApJS, 156, 311

[6] Kelz A., Verheijen M.A.W., Roth M.-M., Bauer S.M, Becker T., Paschke J., Popow E., Sánchez S.F. & Laux U. (2005), PASP, 118, 129

[7] Meijerink, R., Spaans, M. & Israel, F.P. (2007), A&A, 461, 793

[8] Renzini A. (2006), ARA&A, 44, 141

[9] Sánchez S. F., Cardiel N., Verheijen M. A. W., Pedraz S. & Covone G. (2007), MNRAS, 376, 125

[10] van Albada T.S. & Sancisi R. (1986), Phil. Trans. R. Soc. Lond., 320, 447

[11] Verheijen M.A.W., Bershady M.A., Andersen D.R., Swaters R.A., Westfall K.B., Kelz A. & Roth M.-M. (2004), AN, 325, 151

[12] de Zeeuw P. T., Bureau M., Emsellem E., Bacon R., Carollo C. M., Copin Y., Davies R. L., Kuntschner H., Miller B. W., Monnet G., Peletier R. F. & Verolme E. K. (2002). MNRAS, 329, 513