

X-shooter, UV to K band, intermediate resolution, high efficiency spectrograph for the VLT: status report at the Final Design Review

Sandro D'Odorico^{a,*}, Hans Dekker^a, Ruben Mazzoleni^a, Joel Vernet^a, Isabelle Guinouard^b, Paul Groot^c, Francois Hammer^b, Per Kjaergaard Rasmussen^d, Lex Kaper^e, Ramon Navarro^f, Roberto Pallavicini^g, Celine Peroux^a, Filippo Maria Zerbi^h

^a European Southern Observatory, K. Schwarzschild Str. 2, 85748 Garching bei München, Germany

^b GEPI, Observatoire de Paris,, 5, place Jules Janssen 92195 Meudon Cedex, France

^c Radboud University, P.O. Box 9010, Nijmegen, Netherlands

^d Niels Bohr Institute for Astronomy, Physics and Geophysics; Astronomical Observatory
Juliane Maries Vej 30, 2100 Copenhagen, Denmark

^e Sterrenkundig Instituut, Univ. of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, Netherlands

^f ASTRON, NOVA, P.O. Box 2, Dwingeloo, Netherlands

^g INAF, Viale del Parco Mellini 84, 00136 Roma, Italy

^h INAF, Osservatorio di Brera, Viale. E. Bianchi 46, 22055 Merate, Italy

ABSTRACT

X-shooter is a single target spectrograph for the Cassegrain focus of one of the VLT UTs where it will start to operate in 2008. The instrument covers in a single exposure the spectral range from the UV to the K' band. It is designed to maximize the sensitivity in this spectral range through the splitting in three arms with optimized optics, coatings, dispersive elements and detectors. It operates at intermediate resolutions ($R=4000-14000$, depending on wavelength and slit width) with fixed echelle spectral format (with prism cross-dispersers) in the three arms. The project has completed the Final Design Review in June 2006. In this status report, the overall concept is summarized and new results on the dichroics, the active flexure compensation system, the operation modes and the expected performance are given. The instrument is being built by a Consortium of Institutes from Denmark, France, Italy and the Netherlands in collaboration with ESO. When in operation, its wide spectral range observing capability will be unique at very large telescopes.

Keywords: ESO VLT, spectrograph

1. INTRODUCTION

In response to the ESO Call for Proposal for 2nd generation VLT instrument in November 2001, four groups expressed the interest to develop the so-called X-shooter instrument., a single target spectrograph for the Cassegrain focus of one of the UTs of the VLT. Following a phase of negotiations among the different proponents and ESO, a Consortium was formed to carry out a feasibility study and, when the project was finally approved in December 2003, to build the instrument. The X-shooter consortium includes institutes in four European countries and ESO. Table 1 shows the X-shooter consortium structure. National Agencies and Institutes contribute to the project with a very significant share of the cost (~ 75% of the manpower and 80% of the hardware). This has permitted a rapid advancement of the project which has been decoupled from the limitations on the cash flow coming from the VLT instrumentation budget.

The initial requirements on the instrument can be synthesized as follows:

- It had to cover a very wide wavelength range (U to K' band) in one observation,
- The sensitivity had to be maximized in the overall range through use of optimized coatings, gratings and detectors

* sdodoric@eso.org, phone : +49-89-32006239

- and the location at the Cassegrain focus of an 8-m UT,
- It should operate at a spectral resolution $\mathfrak{R}= 5000-10000$, depending on the spectral band and adopted slit width, sufficient to address quantitatively a vast number of astrophysical applications while operating in a background-limited S/N regime with the effect of absorption and emission lines originating in the Earth's atmosphere being minimized
- It shall make use of technology that can be rapidly deployed. Our fast schedule calls for commissioning X-shooter at the telescope in Q2/2008 .

Table 1 - X-shooter Consortium Structure

Institute	Management	Main Deliverables/ Areas of Responsibility
European Southern Observatory	P.I.: S.D'Odorico P.M.: H. Dekker	Project global management and system engineering, detector systems, flexure compensation, data flow system overview
Niels Bohr Inst. for Astronomy, Physics & Geophysics , Copenhagen University	P.I. & P.M.: P.Kjaergaard Rasmussen	Backbone and associated subsystems, UVB arm, overall FEA, control electronics
GEPI Lab, Observatoire de Paris ; AstroParticule et Cosmologie Lab., Université de Paris VII	P.I.: F. Hammer P.M.:I. Guinouard	IFU, Data Reduction Software
INAF: Osservatori di Brera, Catania, Palermo & Trieste	P.I.: R.Pallavicini P.M.: F. Zerbi	Visual arm, UVB and VIS optics, instrument control software
Astronomical Inst., Univ. of Amsterdam; ASTRON; Dept. of Astronomy, Nijmegen Univ.	P.I.: L.Kaper P.M.: R. Navarro	Infrared Arm; contribution to DRS

The name X-shooter has been inspired by the instrument capability to observe in a single shot a source of unknown flux distribution and redshift.

A report on the X-shooter as it stood after the Feasibility Study was presented at the 2004 SPIE Astronomical Instrumentation meeting [1]. In this paper, we recall the concept and concentrate on the new instrument developments as of the Final Design Review which took place in February 2006.

2. SCIENTIFIC DRIVERS

The scientific objectives of X-shooter have been elaborated during Phase A and they are briefly recalled below:

- Spectral properties and gas kinematics of protostars
- Properties of cool white dwarfs
- The nature of neutron stars in close binary systems
- Physical processes in the atmospheres of brown dwarfs
- Properties of core-collapse supernovae; Type Ia supernovae to $z=1.7$
- Gamma-ray bursts as high-energy laboratories and cosmological probes of the intergalactic medium
- The role of faint emission line galaxies in the redshift interval $z = 1.6-2.6$
- Properties of high mass star formation and massive galaxies at high z
- Metal enrichment in the early universe through the study of high z absorption systems
- Tomography of the Intergalactic Medium through the observations of faint background QSOs

3. PROJECT UPDATE

3.1 Overall instrument concept

Figure 1 illustrates in a schematic way the X-shooter instrument and its subsystems. The calibration lamps are located in the upper section of the instrument. Mechanical slides can insert above or at the focal plane calibration lamp mirrors, a small integral field unit [2] reformatting a 1.8" x 4 " area into a slit of 0.6" x 12 " or mirrors feeding an acquisition

and guiding camera. After the telescope focal plane the light beam is split in three spectral ranges (UVB, Visual and NIR) by two dichroics and focused by auxiliary optics on three separate slits. The maximum slit length is 12 “ for all arms. The transfer optics in the UVB and Visual arms include atmospheric dispersion correctors. All three arms include piezo mirrors for flexure compensation (see section 3.4). The three spectrograph arms each include fixed echelle grating and prisms cross-dispersers, providing full spectral coverage in a single exposure with a spectral resolution between 4000 and 11000 depending on the slit width and the spectral arm. Each arm has optimized optics, coatings, dispersive elements and detectors to maximize efficiency.

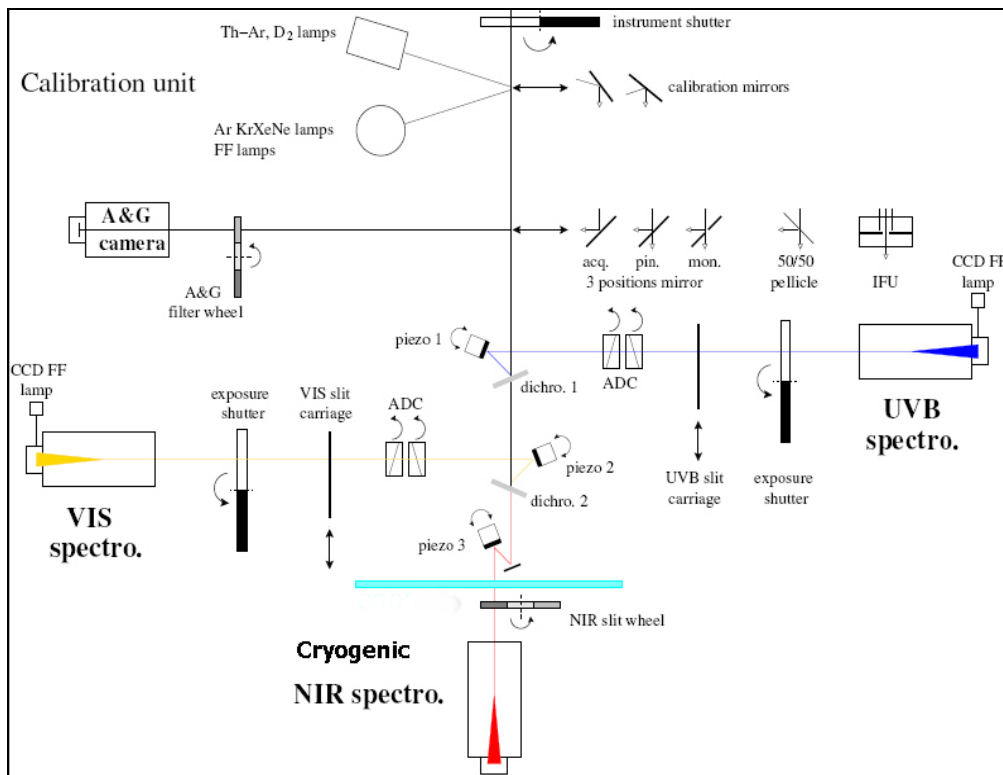


Fig.1 Functional scheme of the X-shooter

The small number of moving functions and instrument modes and the fixed spectral formats make the instrument simple and easy to operate and permit a fast response. With its capability to observe single objects over a wide spectral range at the sky limit, the X-shooter will be an unique facility among 10-8m telescopes.

3.2 Opto-mechanical design

With respect to our last report on the project [1], the overall optical design has not changed. The three arms are all based on the 4C layout (Collimator Compensation of Camera Chromatism), a variation of the white pupil layout adopted successfully in UVES and in many other ESO and non-ESO instrument. Advantages and limitations of the 4C layout have been already discussed in [1,8]. The medium resolution, prism-cross-dispersed, low blaze echelle application in the X-shooter appears as the ideal niche to apply for the first time this concept. Figure 2 shows the layout of the Visual spectrograph. The UVB spectrograph design is very similar. Both have a collimated beam size of 10cm with the larger camera optics at 80mm. In the case of the NIR arm, the 4C concept has been modified to decrease the overall size through a two-mirrors collimator. The NIR collimated beam is 85mm. Three prisms, one 35° Infrasil and 2 22° ZnSe insure an uniform separation of the echelle orders. With respect to the design presented at PDR, a slower

camera (F/2.1) has been introduced to match a 2K x1K section of a 2K x 2K Hawaii 2RG array (18 μm pixel). The detector covers the full spectral range from 1.05 to 2.3 μm . with a good sampling of the slit (see figure 7). More details on the optical design are given in ref. 5 .

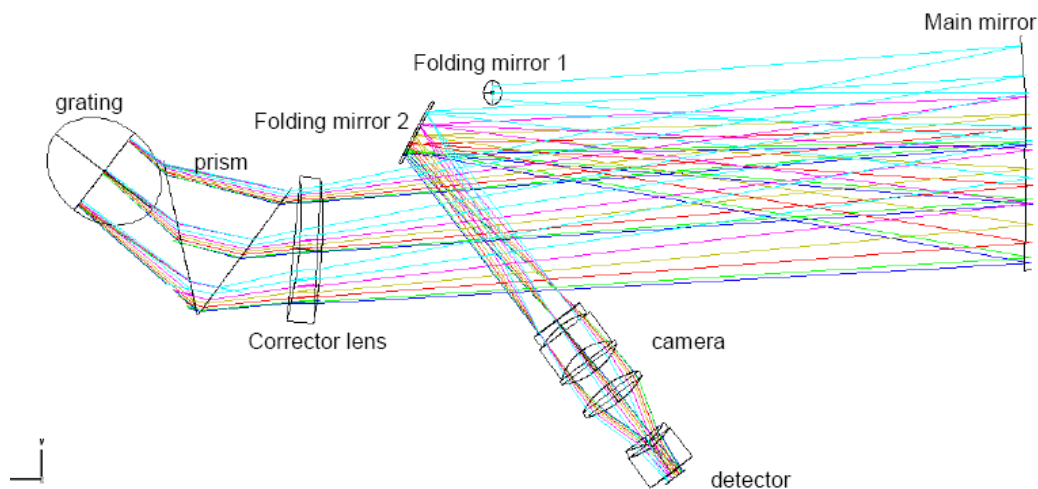


Figure 2. The so-called 4C (Collimator Compensation of Camera Chromatism) layout has been adopted for all three spectrographs. The VISUAL arm is shown here.

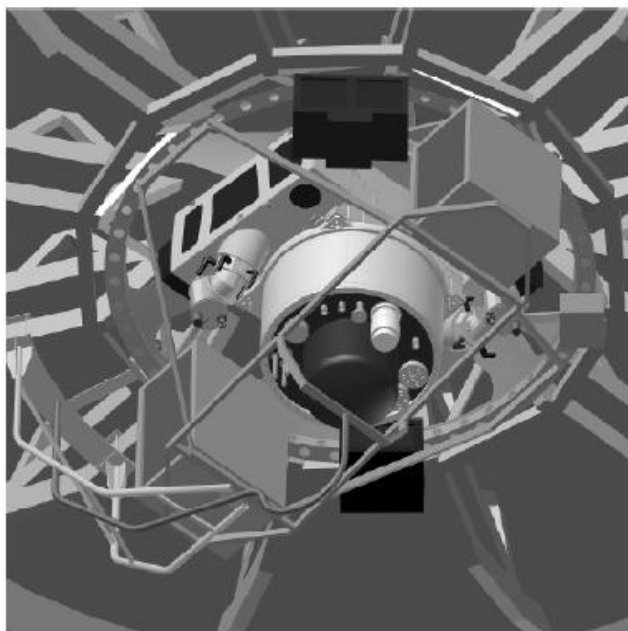


Figure 3. X-shooter mounted at the Cassegrain focus of the UT of the VLT. The NIR spectrograph cryostat is mounted at the bottom, the UVB and VIS ones at the side. Electronic cabinets and detector control systems are attached to the outer structure.

The basic mechanical concept has also remained unchanged with respect to PDR but all subsystems have advanced to detailed drawing level [3,4].

The most significant changes concern the cryostat of the NIR spectrograph. The closed cycle coolers, the vibrations of which can affect interferometry, have been replaced by passive cooling with LN2. The structure of the backbone has

been strengthened to keep the relative motions of the slit to a minimum. The mechanical support of the electronic cabinets has been modified to satisfy the earthquake requirement. FEA models have been developed for all of the main subsystems and then combined for the full instrument . They have been used to explore the ways to optimize the stability while keeping the total weight well within the 2500 kg limit.

3.3 Dichroics

Two dichroics in series are key components of the instrument . They split the incoming beam to feed the three separate spectrographs. We have chosen to have the first dichroic to reflect the UVB light because this reduced the risk of efficiency oscillations in that spectral band where these effects can be stronger.

The nominal cut wavelength (T=50%) of the first dichroic (D1) is at 557.7nm, in correspondence of a strong sky [OI] emission line. The nominal cut wavelength of the second dichroic has been chosen at 1010nm in order to maximize the efficiency within the highest echelle order of the NIR arm spectrum (free spectral range 1026-1068nm).

The dichroics have been manufactured by SAGEM (FRA) and Advanced Technology Coating Ltd (UK) and have been already delivered to ESO. Both dichroics have been realized by means of deposition of multi-layers dielectric coating onto a substrate made of Infrasil® Fused Silica; the coatings have been optimized for an angle of incidence of 15°, which was chosen as a compromise between the mechanical constraints and the request to minimize the width of the transition region when T passes from 20% to 80% (<25nm for D1 and <35nm for D2). Wide band AR coatings have been applied on the rear faces of both dichroics.

Table 2 gives the spectral characteristics of D1 and D2 (AR coatings are included) as measured by the manufacturers. Figure 4 shows the combined efficiencies of the two dichroics in series .

Table 2. Absolute and average Reflectivity and Transmission of the two X-shooter dichroics.

D1 (SAGEM)			D2 (ATC)		
Parameter	Wavelength Range	Value	Parameter	Wavelength Range	Value
R _{abs}	300-528	>96%	R _{abs}	550-980	>94.4%
R _{avg}	300-528	99%	R _{avg}	550-980	98.4%
T _{abs}	591-2300	>90%	T _{abs}	1060-2300	>96.5%
T _{avg}	588-2300	96%	T _{avg}	1060-2300	98.8%

The average efficiencies of the dichroics per arm are 99.0%, 93.9% and 95.1% respectively for the UV-B (300-528nm), VIS (588-980nm) and NIR (1060-2300nm) arms, which allow fulfilling the original requirement of an average efficiency of the pre-slit optics of 80% outside the crossover range.

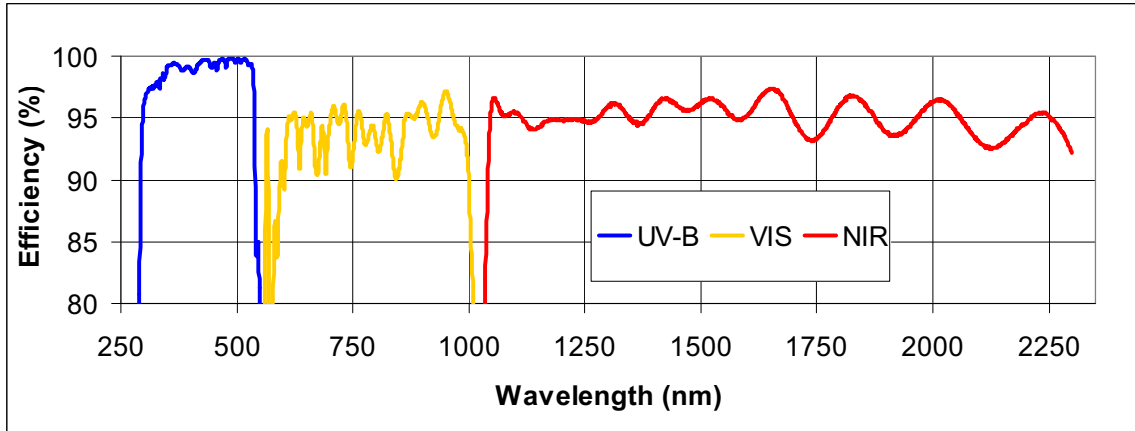


Figure 4: Efficiency of the combined dichroics

3.4 Active flexure compensation of the slit relative motion

During the final design phase, the opto-mechanical design teams have built a Finite Element Model (FEM) and analyzed the deformations of the mechanical structure. In this instrument two type of motions are important : the drift of the three slits with respect to the reference point in the focal plane of the telescope (affecting the relative efficiency of the spectrographs) and the motion of the image of the three slits on the corresponding detector slits (affecting the quality of the spectra) when the telescope points to different coordinates in the sky. Using the FEA results the translations and rotation of the optical elements due to flexures in each of the three paths were predicted and used in combination with Zemax Optical Design Program to compute the motions of the three slits and on the detectors.

In all three spectrographs, the motions of the image of the slit on the detector are predicted to be within specifications (less than one detector pixel between any orientation).

As for the relative motions of the slits, the analysis did show that while the UVB and VIS slits [3] might marginally meet the specifications (slits to remain stable to < 0.2 arcsec along the slit direction and to < 0.08 arcsec in the perpendicular direction) the relative movements of the NIR slit clearly exceeded the requirements [ref. 4 and Fig 5]. This result is not surprising since the NIR spectrograph is by far the heaviest unit, is mounted at a longer lever arm from the Cassegrain flange and uses reflecting optics to relay the Cassegrain plane to the cold slit plane (Fig.1).

In order to be sure to meet the stability requirements at any position in the sky, we have implemented a scheme for Active Flexure Compensation (AFC). It is based on three piezo tip-tilt mirrors (see Fig.1). AFC works via a quick analysis of the instrument distortions at the position and at the time of the observations. After the telescope has completed slewing to the target, the instrument control software will:

- 1) Take an arc spectrum with each of the three spectrographs, using a reference pinhole in each of the three slit units. Each reference pinhole materializes the center of the slit .
- 2) Take an arc spectrum of backbone + spectrograph, using a reference pinhole this time in the A&G slide in the telescope focal plane (“pin” in Fig. 1).This reference pinhole is linked to a position in the Acquisition CCD. A wide slit is selected in the slit units to avoid vignetting of the image of this reference pinhole by the slit edges due to flexure and ADC axis wobble
- 3) Analyze the misalignment between images 1) and 2); correct by applying the proper offsets to the three tip-tilt mirrors.
- 4) After the telescope Active Optics process is finished, take an image with the A&G camera and interact with the user to perform object acquisition and object centroiding

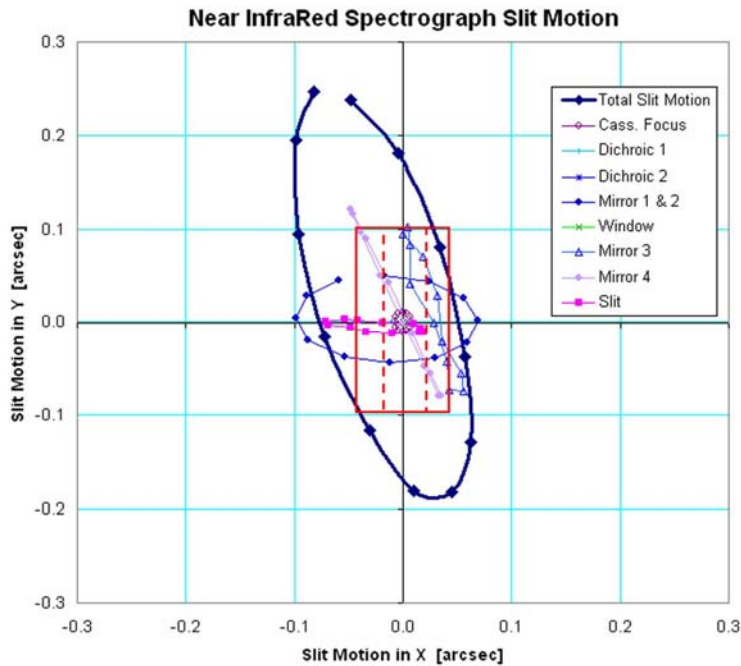


Figure 5. Predicted motion of the image of the NIR spectrograph slit in the Cassegrain focal plane when rotating the instrument about its axis at a zenith distance of 60 degrees (solid line with diamonds). The scale is $520 \mu\text{m}/\text{arcsec}$. The slit is aligned with the Y-direction. Individual contributors to the total slit motion are also shown (thin lines; see legend) M1-M2 are warm folding mirrors, M3 and M4 cold ones. The rectangular boxes show goal and specifications for the slit motion [4 and reference there in].

Steps 1-3 will take about 70 seconds and do not require any user interaction. The duration is mostly determined by lamp exposure times and speed of mechanisms. However, since AFC will run in parallel to the telescope Active Optics, it will generally not add observing time overheads on top of those imposed by the telescope

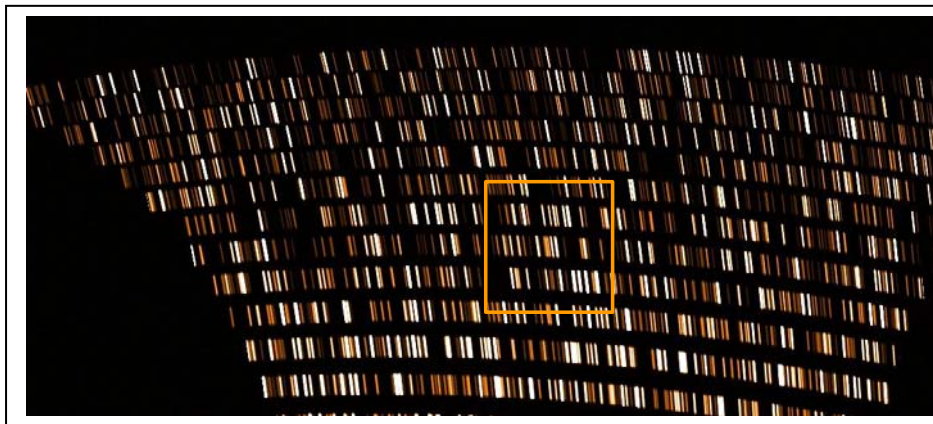


Figure 6. Simulated ThAr spectrum of the calibration lamp in the VIS arm. The box shows a 500×500 readout window. This spectrum was simulated for a 12" long slit; for the flexure measurement a pinhole of 0.5" will be used. As also explained in the text, backbone flexure is measured and corrected by comparing positions of lines in two spectra: one taken with a pinhole in the spectrograph slit unit, and one taken using the alignment pinhole which can be inserted in the telescope focal plane with the A&G mirror slide.

A simulated X-shooter arc spectrum is shown in Fig. 6. The UVB and VIS CCDs will be read at 600 kpix/sec in less than 1sec since only a small readout window, centered on the nominal zero-deviation wavelength of the ADC, is required. In the NIR, the standard ESO IR Array Controller reads the complete Hawaii 2RG chip in less than 1 sec, but also here only lines near the center of the array will be selected to compute the AFC corrections.

The expected relative motions of the slits due to flexure or temperature variations during the exposure time (< 1 hr, even for multiple exposures) are predicted to have negligible effects on the efficiency and image quality of the spectrographs.

3.5 Observations, Calibration and Data reduction pipeline

The target acquisition will be done by centering the object on a given reference pixel on the A&G camera. This reference pixel will correspond to the position of the reference A&G pinhole with respect to which the slit center in each arm is aligned at the beginning of each observation during the AFC calibration procedure described in the previous section. This procedure to center the object on the slits takes into account the effects of atmospheric dispersion (difference between the photometric band of the acquisition image and the reference wavelength of the ADCs). For very faint targets, the possibility to offset from a bright reference object will also be offered.

Different observing strategies will be supported by dedicated Observing Templates:

- a Single Shot with Synchronized Exposures. This is the simplest “point & shoot” observing method. It takes a single exposure in each arm using one of the slits or the IFU with exposures being synchronized at mid-time. The only free parameter is the exposure time in each arm.
- a Staring mode to take a sequence of exposures at a given fixed position on the slit or the IFU. The number of exposures and exposure time in each arm are free parameters.
- a Nod & Jitter mode which allows to alternate between two positions along the slit with the possibility to add a small random offset around each position. This classical infrared observing technique will be especially suited to allow the best subtraction of the strong varying OH sky lines.
- an On-Off mode which will allow to alternate between the science object and the sky at a given offset position. This method is dedicated to observations of extended objects (both for slit and IFU).

In addition, a generic observing template which allows the programming any free sequence of offsets will be available both for slit and IFU observations.

The data reduction pipeline will fully support the standard observing modes (not the free sequence), producing flux and wavelength calibrated 2D spectra with associated errors. In case of IFU observations, 3D (x, y, λ) calibrated data cubes will be produced. Whenever possible, a 1D spectrum will also be optimally extracted. An extensive set of Quality Control (QC) parameters will be produced along the data reduction chain to check the quality of the processed data and to monitor the performances of the instrument. The Data Reduction Software will be integrated into the ESO Data Flow System and will use the ESO Common Pipeline Library. It is fully described in [6].

Besides the usual set of calibrations (bias, flat-fields, telluric standards, radial velocity standards), the wide wavelength range, the spectral format with highly curved orders and tilted lines and the image slicer of the X-shooter require special attention, in particular:

- The accurate determination of the mapping between detector pixels and the wavelength-spatial scale space is highly critical for accurate sky subtraction. This mapping will rely on a set of arcs exposures through a dedicated multiple pinhole masks available in the slit carriage of each spectrograph.
- The relative distance between the slices of the IFU to allow an accurate reconstruction of the data cube. This will be calibrated by placing a star in between two adjacent slitlets (2 pointings to calibrate the 3 slitlets). Comparison of the centroid of the star in the spectrum obtained in the two neighboring slitlets will give a measure of their relative distance.
- The spectrophotometric calibration from 300nm to 2400nm (with a $<10\%$ accuracy goal) is quite challenging and complicated by the lack of suitable spectrophotometric standards in the NIR. It is planned to organize an observing campaign at ESO to produce a catalogue of standard stars adapted to X-shooter. The full calibration will most likely require the observation of two stars (one for the UVB-VIS range, one for the VIS-NIR range). This area is still under investigation.

These scientific calibrations will be obtained on a regular basis as part of the X-shooter Calibration Plan. In addition to this, instrument monitoring and health check procedures such as full detector characterization, alignment and sensitivity checks have been defined.

3.6 Predicted performance

We have carried out extensive simulations of the instrument performance taking into account the contractually specified performance of the different optical subsystems and the detectors. In the case of the dichroics and of the detectors the values refers to the actual components which will be used in the instrument. Figure 7 show the expected resolution and sampling as a function of slit widths . The computation took into account the finite pixel size, the camera focus error, the electronic LSF and the optical component LSF. When the IFU unit is inserted in the focal plane, it creates a pseudo slit of 0.6'' width and the resolutions match the corresponding values.

The expected efficiency of the instrument over its global spectral range is shown in Figure 8. It is higher than for high dispersion spectrographs like UVES at the VLT and HIRES at Keck, while providing parallel coverage of the all spectral range from UV to K'. Taking into account the various sources of noise, we have computed the expected limiting AB magnitudes for the regions between sky emission and listed them in Table 3. The instrument has not been optimized for the K band observations. The thermal emissivity from the telescope and instrument optics in the K band has been assumed at 25%.

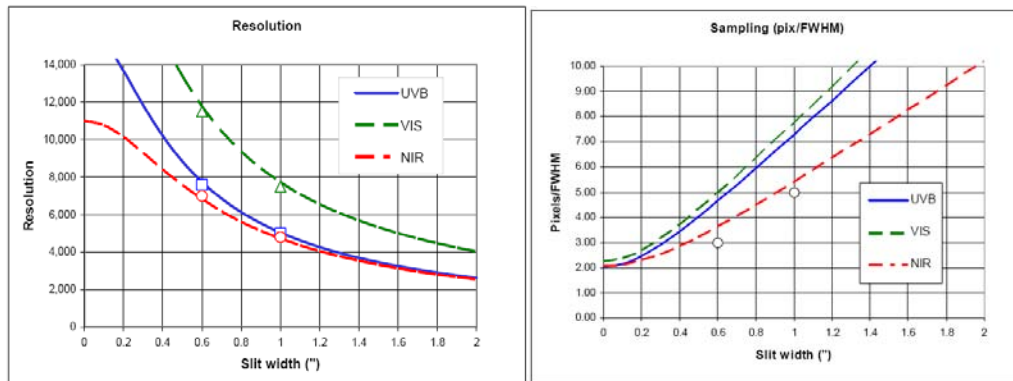


Figure 7. Predicted resolving power and pixel sampling of the three arms

Table 3. Computed limiting AB magnitudes (1 hr exposure, S/N=10 per resolution element)

Band	U	B	V	R	I	J	H	K'
mag	21.5	21.7	21.7	21.6	21.2	20.5	20.8	19.3

4. FUTURE MILESTONES

The Final Design Review of the Backbone , UVB and VIS arms optics had been successfully passed in 2005 and the components have been ordered. The detectors and the control system are already in house.

At the FDR in February 2006, the overall mechanical design of the instrument and its associated software was well received but for a number of items where further work was needed to reach FDR level. The Consortium plans to close these items by June 2006 and to proceed with the procurement of the mechanics and electronics. The three arms will be integrated at the institutes which are responsible for their design and procurement and upon acceptance transferred to ESO for integration with the instrument backbone. Testing of the overall instrument is planned to start in mid 2007 at ESO. Commissioning of the instrument at the telescope is planned for 2 Q 2008 .

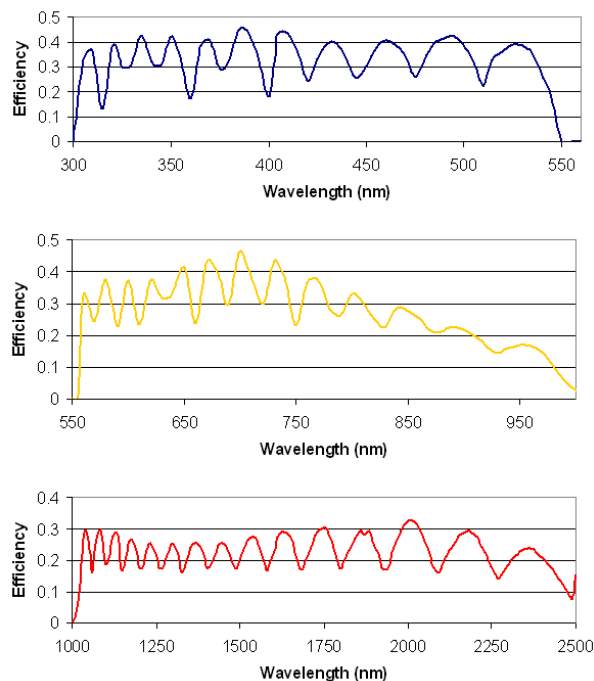


Figure 8. Predicted efficiency of the three arms , from the focal plane to the detector. The wave form of the curves is due to the echelle blaze.

ACKNOWLEDGEMENTS

The X-shooter project team is composed by more than 65 engineers and astronomers distributed at the various Institutes participating to the project in Denmark, France , Italy, the Netherlands and ESO. It is thanks to their qualified contributions and commitment that the project is advancing toward a successful completion. Their names appear in the list of co-authors of the various X-shooter papers at this SPIE meeting quoted in the references.

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