FEROS, the new fiber-linked echelle spectrograph for the ESO 1.52-m telescope

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ABSTRACT

Feros is a new fiber-fed bench-mounted prism-crossdispersed echelle spectrograph for the ESO 1.52-m telescope at the European Southern Observatory (ESO) in La Silla, Chile. It works with a 79 lines/mm R2 echelle grating in quasi-Littrow mode and in white pupil configuration. With two fibers of 100 μm core diameter for the object and the nearby sky, the complete optical spectrum from $370 - 860$ nm is recorded in one single exposure on a 2k×4k thinned CCD with 15 μm pixels. Therefore, the instrument can work in a fixed configuration on the optical bench without movable parts besides the CCD shutter mechanics. For the highest-possible opto-mechanical stability Feros will be housed in a temperature and humidity controlled room in the former Coudé room of the telescope.
The resolving power of $R = 48\,000$ is reached by the use of a newly designed two-slice image slicer which is fed by the two fibers. Alternatively, the sky fiber can be illuminated with a calibration lamp during the whole object exposure to monitor the spectrograph's residual motions for high-precision radial-velocity work.

Feros is built for ESO by a consortium of four European astronomical institutes under the leadership of the Landessternwarte Heidelberg, Germany. Further members of the consortium are the Astronomical Observatory Copenhagen, Denmark, the Institut d'Astrophysique de Paris, and the Observatoire de Paris/Meudon, France.
It is planned that Feros will be fully operational at the ESO 1.52-m telescope in December 1998 and will be available to the community in early 1999.

Keywords: Instrumentation, optical, spectrograph, fiber-link

1. INTRODUCTION

In the new era of $8 - 16$-m telescopes large resources of small to medium size telescopes are set free. In parallel, the need for telescopes with highly specialized instrumentation for dedicated observing programs increases considerably. Since for many scientific programs – especially in stellar astrophysics – the collecting area of the telescope can be of minor importance, but e.g. extended observing time bases or high-precision radial velocity measurements are required, the equipping of existing $1 - 4$-m telescopes with a new generation of dedicated instruments is of extremely high scientific interest.

The **F**iber-fed **E**xtended **R**ange **O**ptical **S**pectrograph (Feros) introduced in this paper is developed by a consortium of four European astronomical institutes for the ESO 1.52-m telescope at the European Southern Observatory (ESO) in La Silla, Chile. Feros is an example for a newly developed state-of-the-art high-resolution spectroscopic facility fiber-linked to a telescope which was commissioned in the late sixties but is already expected to be a workhorse instrument for the stellar astrophysics community.[1]

In this contribution the design of the Feros instrument will be presented in detail with special emphasize on the optical design, which is based on the work of Bernard Delabre at ESO. The opto-mechanical design of Feros is in many respects related to the **U**V-**V**isual **E**chelle **S**pectrograph (Uves[2]) currently under construction for the ESO Very Large Telescope (Vlt).

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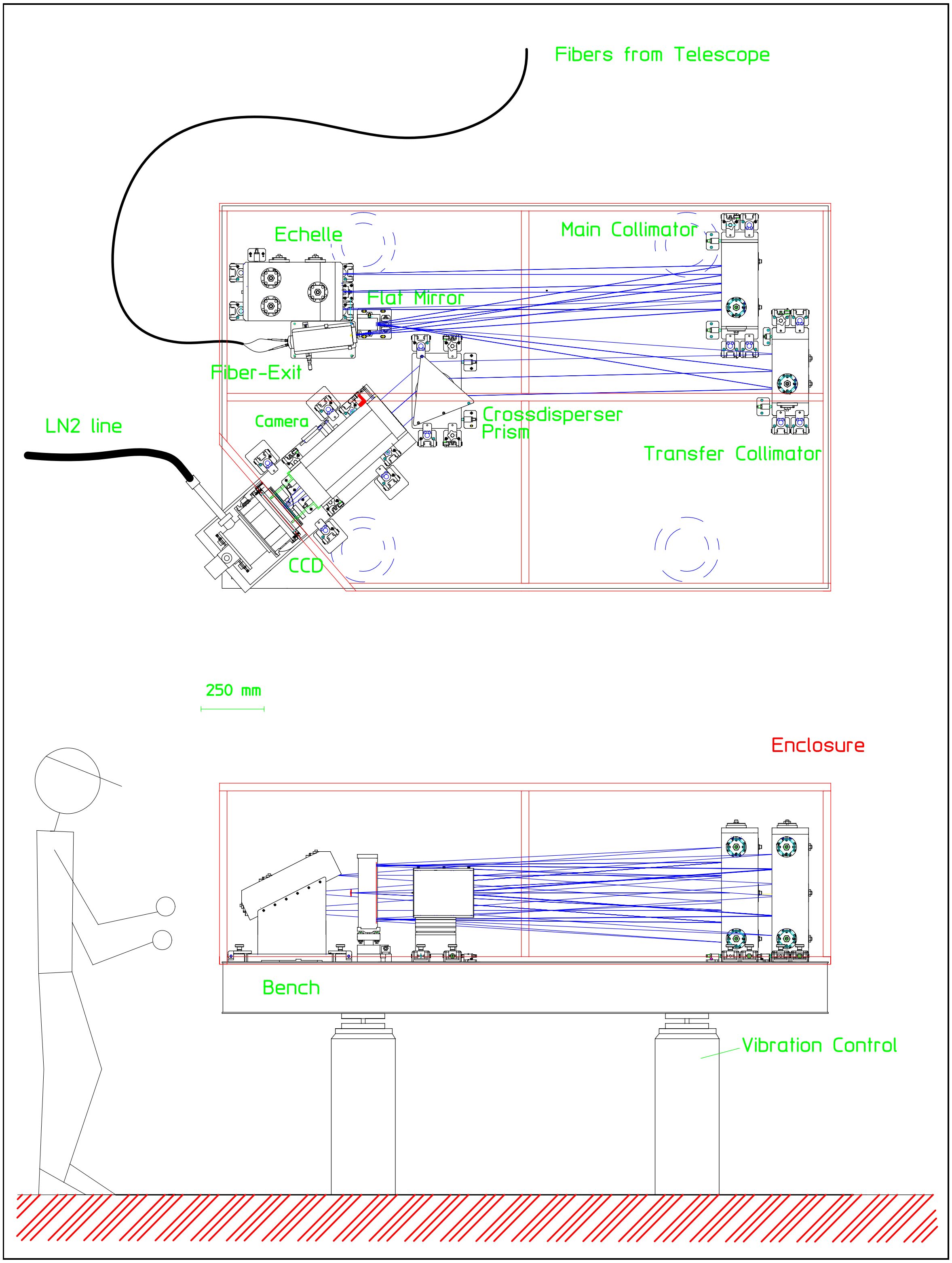

Figure 1. Top and side view of the opto-mechanical layout of FEROS. In the lower figure, the fiber-exit unit and the camera-CCD unit have been removed. The light paths for the center and the two extremes of order #27 ($824 - 853$ nm) are shown.

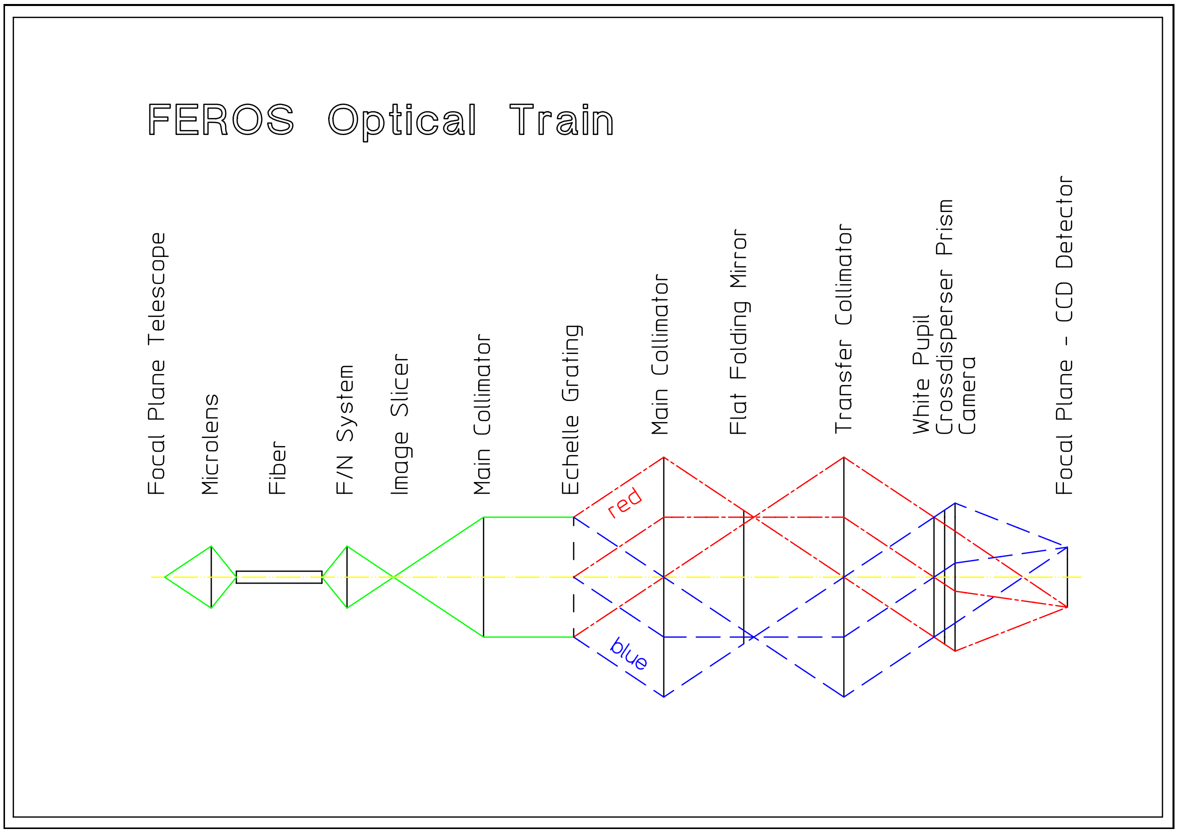

Figure 2. FEROS optical train. The white-pupil configuration can be nicely seen by following the dispersed collimated beam in the red and blue paths after the echelle grating which re-form a white pupil close to the crossdisperser prism.

2. OPTO-MECHANICAL DESIGN

FEROS is a fiber-fed bench-mounted and prism-crossdispersed echelle spectrograph. The opto-mechanical layout of the bench-mounted part of FEROS is shown in Fig. 1. This part of the spectrograph will be located in the former Coudé room of the ESO 1.52-m telescope in a separate temperature and humidity controlled room for high long-term stability. The Cassegrain focus of the telescope is equipped with a classical Boller & Chivens grating spectrograph which will be modified to carry the additional FEROS fiber-entrance unit and a new extended calibration unit usable for both spectrographs. The common slit unit for both spectrographs will allow a change between the two instruments within a few minutes which is an interesting option for spectroscopic programs that e.g. require a pre-examination of the targets with low spectral resolution or high-resolution spectrophotometric observing programs.

A scheme of the complete optical train from the telescope's focal plane to the CCD plane of the FEROS spectrograph is shown in Fig. 2: the light of the object and the nearby sky is coupled via microlenses into two 100 μm fibers in the Cassegrain focus of the telescope. The microlenses convert the f/15 telescope beam into a f/4.6 beam which is best-suited for the fibers. The light is guided via the two fibers of 14 m length to the spectrograph itself where the fiber exit is first converted via a focal-enlarger lens system (F/N-system) to the f/11 focal ratio accepted by the spectrograph. An image slicer in the f/11 focal plane halves the width of the images of the two fibers in the direction of dispersion. For a more detailed description of the fiber link and the fiber-image slicer see below.

The system entrance pupil is re-imaged on the 79 lines/mm R2 echelle grating through the main off-axis collimator. The beam-size of the spectrograph is 136 mm. The MILTON ROY echelle grating is used in quasi-Littrow condition with an off-Littrow angle of $\gamma = 0.6°$. By this, the dispersed light goes back from the echelle to the main collimator and is reflected by the flat folding mirror towards the transfer off-axis collimator. The two off-axis collimators are manufactured by Optical Surfaces Ltd., England, and are cut from a common parent parabolic f/2.2 mirror of 680 mm diameter. The narrow flat mirror for the folding of the beam is located close to the intermediate focus of the two collimators and already acts as an effective baffle for the straylight produced by the echelle grating.

This white-pupil configuration[3] of the echelle and the two collimators plus the flat mirror effectively transfers the white pupil from the grating close to the entrance surface of the LF5 crossdisperser prism where a tilted elliptical white pupil image becomes available. In contrast to a grating, the use of a prism as crossdispersing element provides simultaneous access to the full wavelength range (which in the case of Feros exceeds a factor of 2) together with a high efficiency. Even with the white-pupil configuration the 55° prism has to be very large with a base length of 235 mm and a height of 175 mm. The prism was manufactured by Optical Surfaces Ltd., England, from LF5 glass with low stress-birefringence and homogeneity class H4 and provides wavefront transmission aberrations of less than $\lambda/4$ p-V due to the use of hand polishing techniques. The prism is used in the minimum deviation condition for the spectrograph's central wavelength, i.e., 462.3 nm in order #49.

Finally, the two-dimensional echelle spectrum is imaged by the fully dioptric f/3 camera (see below) onto the detector. The field lens of the camera acts as the entrance window of the CCD continuous-flow dewar. The detector itself is a monolithic thinned and back-illuminated 2048×4096 15 μm pixel CCD by EEV, England.

All lens surfaces are anti-reflection coated with broad-band multilayer coatings; for all mirror surfaces a high-reflectivity UV-enhanced protected single-layer silver coating by Balzers, Liechtenstein, is used. The very large prism was decided to be coated with a broad-band multilayer coating optimized for 45° AoI by Reosc/Sfim, France, which is applied at temperatures less than 60°C but provides a hard and cleanable surface. With efficiencies of 72% for the echelle, 60% for the fiber link (see below), and a peak efficiency of 85% around 500 nm and about 55% at 370 and 800 nm for the CCD, a high detection efficiency of 6% at 370 nm, 21% at 500 nm, and 9% at 900 nm is expected for the Feros instrument (without telescope). The main parameters of the optical configuration and the expected performance for Feros are summarized in Table 1.

Table 1. Main parameters of the optical system of Feros.

Wavelength range	
in one exposure (object+sky)	370 – 860 nm (40 orders, 2 fibers)
Resolving Power (with 2-slice image slicer)	$\lambda/\Delta\lambda = 48\,000$
Entrance Aperture	2.7 arcsec
Fiber input/output Focal Ratio	f/4.6
Spectrograph Beam Size	136 mm diameter
Off-axis Collimators	f/11, cut from one parent paraboloid
Echelle	R2, 79 lines/mm, 154 mm by 306 mm
Crossdisperser Prism	LF5 glass, 55° apex angle
Dioptric Camera	
Wavelength Range	350 – 900 nm
f/#	f/3.0
Focal Length	410 mm
Field Diameter	69 mm
Image quality (E_{80})	$< 25\,\mu$m
Efficiency	$> 85\%$
CCD	$2048 \times 4096, 15\,\mu$m, thinned
Expected Detection Efficiency (without telescope)	6% (370 nm), 21% (500 nm), 9% (900 nm)
Expected Limiting Magnitudes at the ESO 1.52	16 mag in V ($S/N = 10$, 2 h)
	12 mag in V ($S/N = 100$, 2 h)
Expected Radial-Velocity Accuracy	$< 25\,\mathrm{m\,s^{-1}}$, $< 5\,\mathrm{m\,s^{-1}}$ with iodine cell

2.1. The Fiber Link

The fibers have a core diameter of 100 μm and are fed by microlenses on the telescope's side (cf. Fig. 3). Two apertures with 0.29 mm diameter (= 2.7 arcsec in the f/15 focal plane of the ESO 1.52-m telescope) are imaged onto

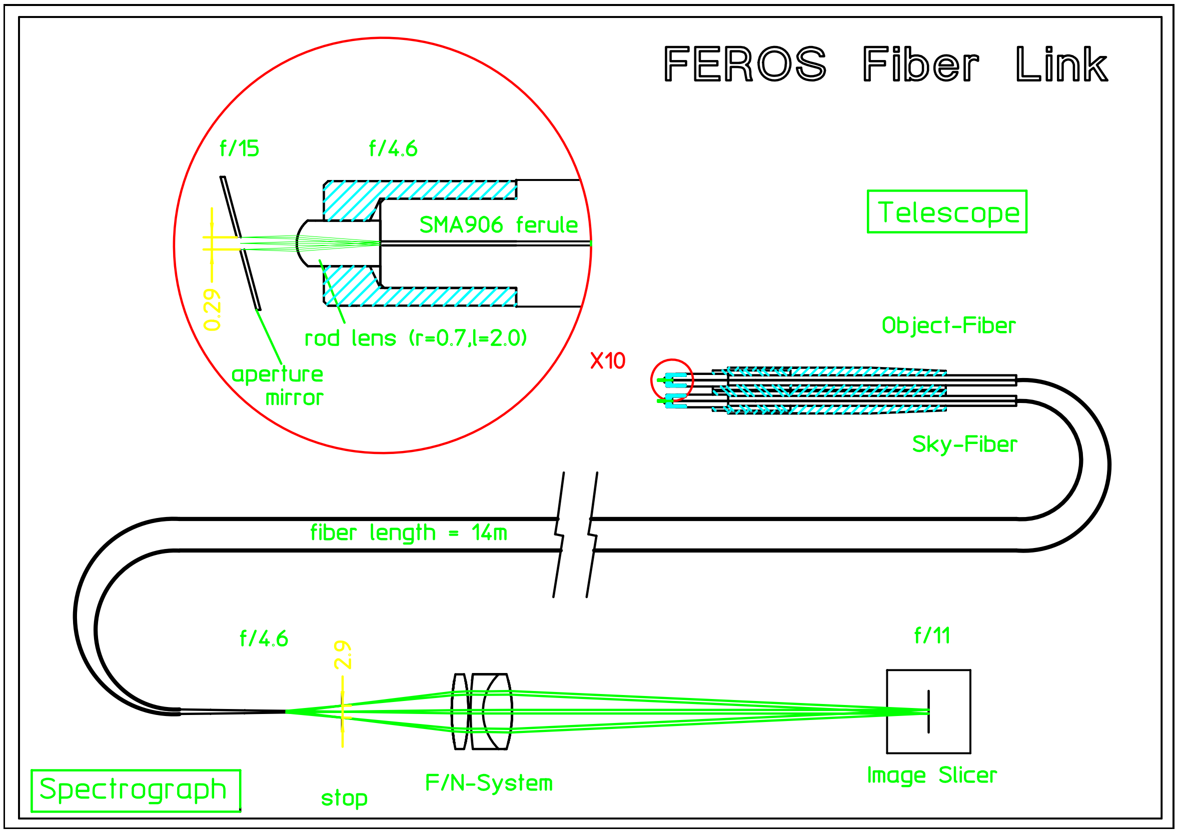

Figure 3. The FEROS fiber link. For details cf. text.

90% of the fibers' entrance-surface diameter resulting in an effective f/4.6 feed which is well-suited to minimize focal-ratio degradation (FRD) effects on the fiber link. The microlens is a rod lens with a radius of curvature of 0.7 mm and a length of 2.0 mm manufactured by FISBA OPTICS, Switzerland. It is directly glued with the flat surface to the fiber entrance surface. The microlens and the fiber are mechanically mounted in a modified SMA 906 connector.

The polished fiber exits are left blank and are re-imaged by the F/N-system produced by SILL OPTICS, Germany, which converts the f/4.6 fiber beams to f/11 beams accepted by the spectrograph. The F/N-system produces images of the fibers enlarged to 240 μm at the intermediate focus. Therefore, the image slicer described below is located at this intermediate focus and defines the "entrance slit" of the spectrograph.

The fiber coupling efficiency for an input/output focal ratio of f/4.6 is expected to be better than 85% for a fiber with a small FRD. The CERAM OPTEC 100/110 WF fiber which was first selected for the FEROS fiber link provides a high transmission from UV to IR free of internal absorptions but was recently found to provide a low coupling efficiency of 65% under the given f/4.6 input/output conditions. Assuming that a suited replacement of this fiber can be found, the total efficiency of the complete fiber link including the microlens, 14 meters of fiber, the F/N-system, and the AR-coated image slicer is estimated to 60%.

2.2. The Fiber-Image Slicer

An image slicer (IS) is crucial for the FEROS spectrograph to obtain a resolving power of $R = 48\,000$. The FEROS IS is basically a Bowen-Walraven image slicer[4] which was modified to slice simultaneously the two beams emerging from the object and sky fibers with a minimum of defocusing introduced by the optical path differences (OPD) inside the slicer. Therefore, an image slicer which merges two individual slicers in one was proposed to be placed at the intermediate f/11 focus feeding the FEROS spectrograph. This integration of two individual slicers in one device was easily done by using *air grooves* on the entrance prism of the slicer which provide the needed internal reflection of the sliced beams and control the height of the sliced output images.

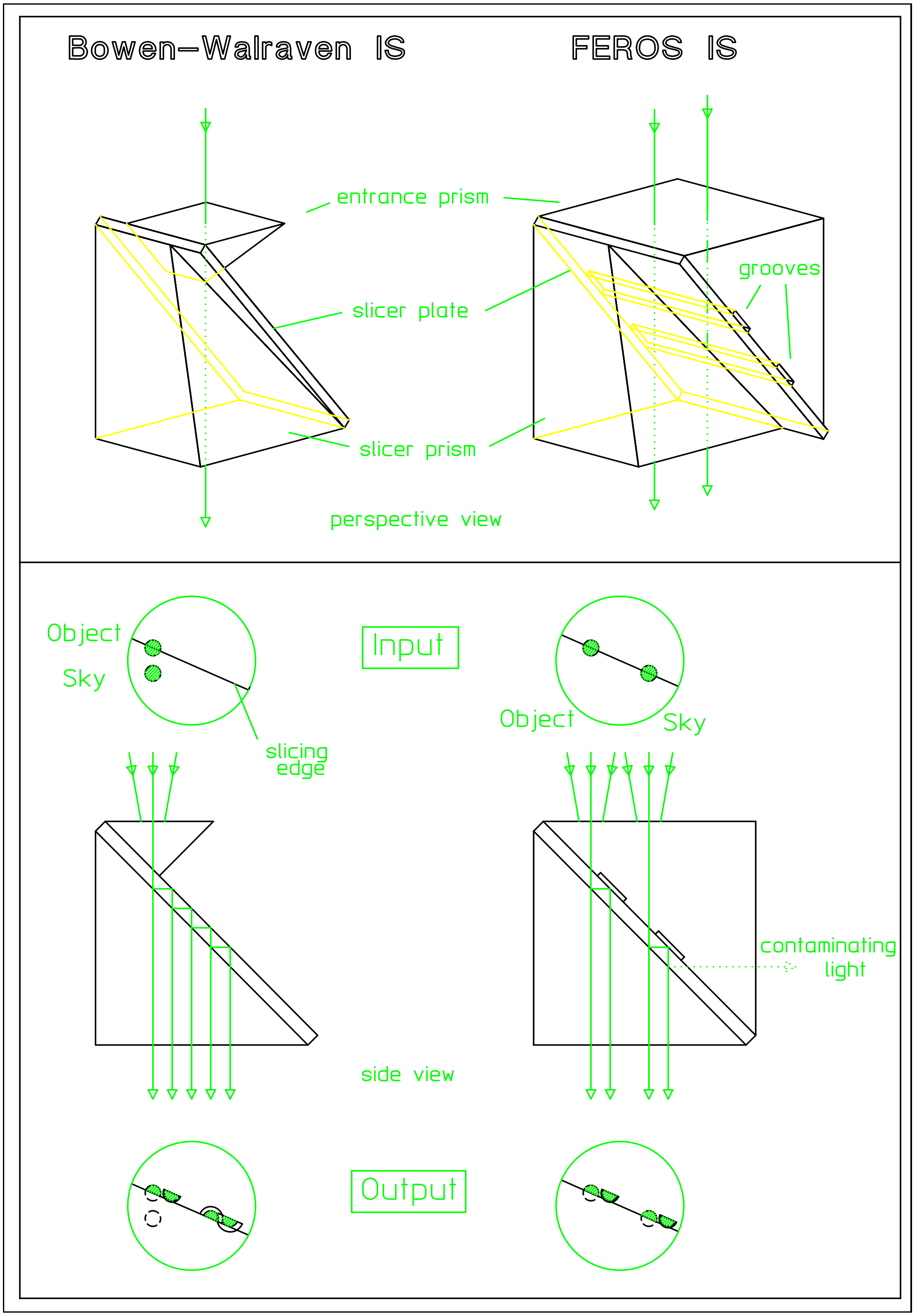

Figure 4. The FEROS IS (right) in comparison with the classical Bowen-Walraven IS (left). For both cases the possibility to slice the images of two fibers is shown. Note that the FEROS IS minimizes the image blur of the slices.

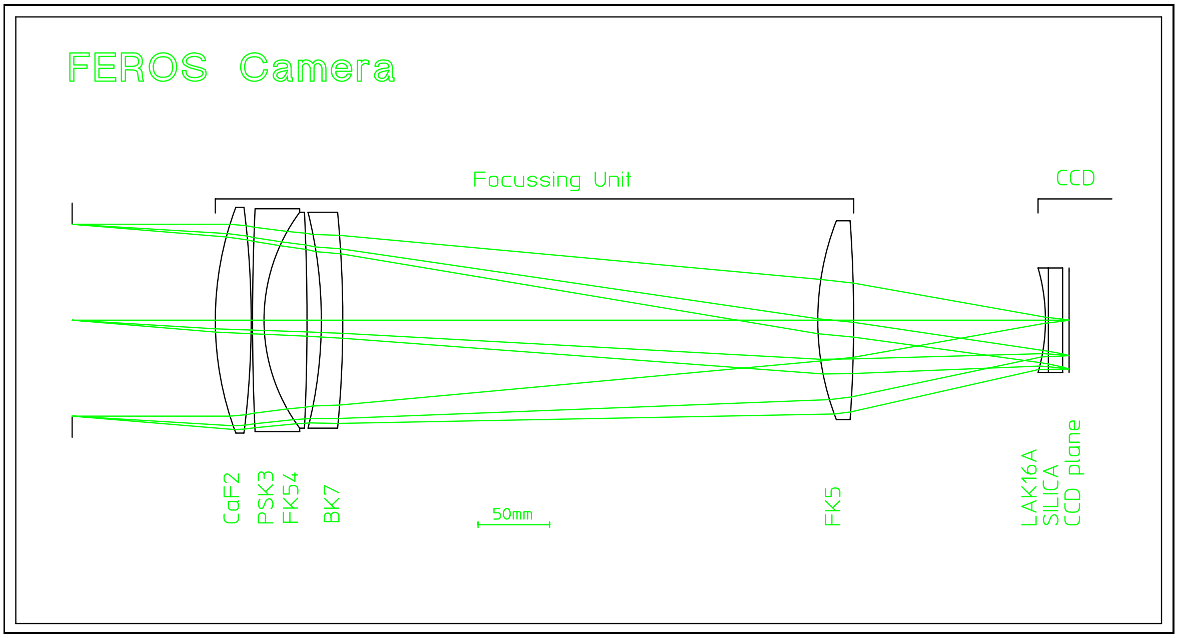

Figure 5. Layout of the FEROS camera. For details cf. text.

Figure 4 shows the layout and function of this IS in comparison with a classical Bowen-Walraven IS. For a detailed description and discussion of the FEROS IS see Ref..[5] A prototype and the final slicer were successfully manufactured by KAUFMANN PRECISION OPTICS, Crailsheim, Germany.

2.3. The Dioptric Camera

The FEROS spectrograph camera (cf. Fig. 5) is a fully dioptric lens optimized for the extended wavelength range of $350 - 900$ nm. It is an effective f/3.0 system with a focal length of 410 mm, a field diameter of 69 mm, and a clear aperture of 178 mm. The system uses a large CaF_2 entrance lens and is optimized without lateral color correction. It reaches an 80% encircled energy spot diameter of $E_{80} < 25\,\mu$m over the whole $\pm 4.8°$ field. Due to the use of UV transmitting glasses and broadband anti-reflection coatings a total transmission efficiency of $> 85\%$ should be reached over the full wavelength range. The camera is manufactured by FISBA OPTICS, Switzerland, with the lens coatings subcontracted to BALZERS, Liechtenstein.

2.4. Image Analysis of the System

Figure 6 shows the results of an image analysis of the complete bench-mounted part of the optical system of FEROS. The two half-moon shaped images are introduced by the two-slice image slicer; the tilt of the slit images is caused by the off-Littrow angle of 0.6° in the system. The image analysis allows to estimate the amount of vignetting introduced in the system which is found to be $\leq 10\%$ in the extreme corners of the CCD. In addition, the image analysis allows to measure the expected degradation of the spectrograph resolution at the different field positions. It is found that at the field center the slit width equals 2.2 pixels and over the whole field a maximum resolution degradation of 10% has to be expected at 2/3 of the maximum field in the central order.

2.5. The Spectral Format

A simulation of the fixed two-dimensional echelle spectrum on the $2k \times 4k$ $15\,\mu$m detector is shown in Fig. 7. This simulation includes the wavelength dependent intensity distribution of the light source, the wavelength dependent transmission of FEROS itself, the two-beam two-slice image slicer, models for the blaze function, for the straylight distribution, and for the photon and detector noise. This simulation runs in the ESO-MIDAS software environment and is primarily used for the development of the online data-reduction and instrument-simulation software.

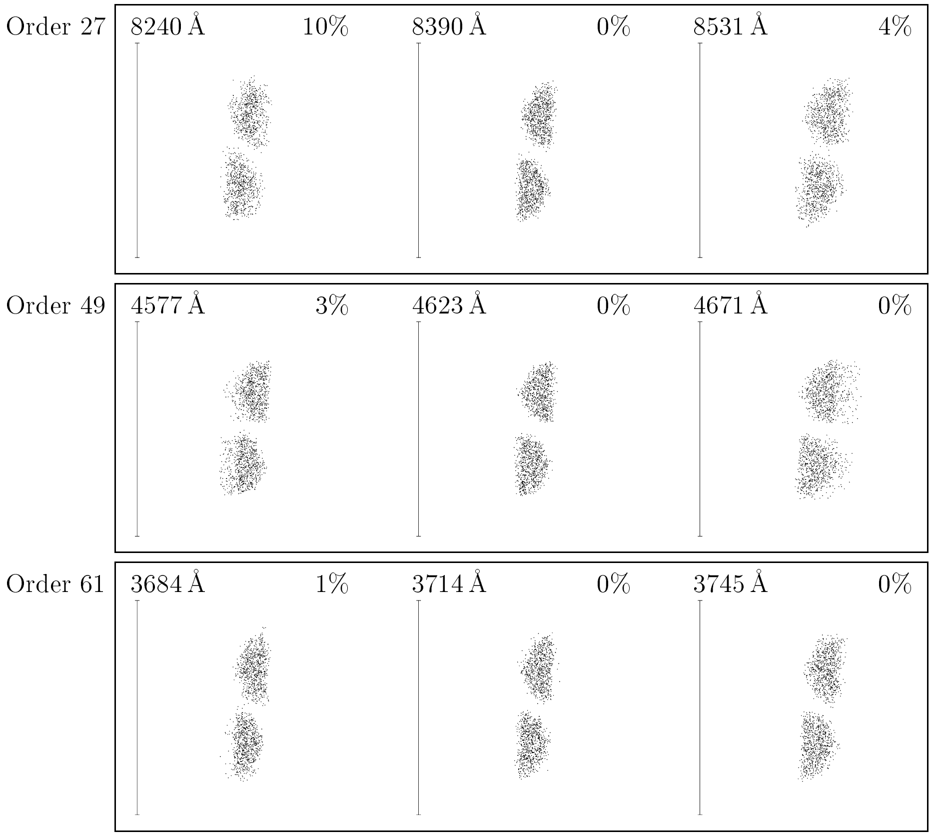

Figure 6. Image analysis of the optical system from fiber exit to detector. The scale bars equal 15 pixels (0.225 mm). The results for the center and the 50% points of the central and the extreme red and blue orders are shown. The percentage figures indicate the respective amount of vignetting of the system.

The prism crossdisperser provides a minimum order separation of 30 pixels in the extreme red orders which leaves enough interorder space for the background determination even with two sliced fiber images per order. The prism crossdisperser further introduces a considerably strong curvature of the echelle orders which is clearly visible in Fig. 7.

A special complication of the spectral format is introduced by the image slicer. As seen in the in Fig. 4 and the image analysis (Fig. 6) this device slices the circular outputs of the two object and sky fibers into two 'half moons' which effectively halves the equivalent slit width in the main dispersion direction. The equivalent slit height was chosen to be 4.5 times the slit width which leaves a quite small gap between the two half moons. The individual slit images will be sampled on some 2 by 10 pixels on the CCD detector. Therefore, a double-peaked crossdispersion slit profile together with curved orders has to be handled by the data-reduction software, which requires special care for the order definition and the optimum extraction algorithms.

2.6. The Mechanical Design

The mechanical design of Feros follows in many parts the design of the Uves instrument for the Vlt and consequently uses standard techniques for bench-mounted instrumentation. The echelle grating and the off-axis collimators are mounted in quite sophisticated kinematic 6-point mounts which allow an independent alignment of the optics in all degrees of freedom; for the small optics in the fiber-exit unit (fibers, F/N-system, and image slicer) standard industrial mounting and positioning elements are used.

The spectrograph is built on a passively vibration controlled optical bench by Newport, USA, and is thermally, light and dust protected by a simple enclosure, but additionally will be housed in a separate isolated light-tight room, which is actively temperature and humidity controlled. This room with the spectrograph is located in the former Coudé room of the ESO 1.52-m telescope.

The FEROS instrument will run in a fixed configuration, i.e., no changes of the configuration, e.g. of the wavelength range, are allowed (and needed) and consequently, *no* movable or remotely controlled parts besides the CCD shutter are present in the bench-mounted part of the instrument. The CCD detector will be equipped with a standard ESO-VLT continuous-flow cryostat (see Ref.[6] Fig. 1) supplied with liquid nitrogen from a nearby vessel with a capacity for about 4 weeks.

All these precautions are taken to ensure a minimum physical interaction with the instrument during operation and therefore, to ensure a maximum long-term stability of the spectrograph.

3. INSTRUMENT HANDLING

3.1. The Observing Modes

For the observations with FEROS, only three observing modes will be provided:

1. `Object + Sky`
2. `Calibration` (Flatfield and Thorium-Argon)
3. `Object + Calibration`

For the latter mode, the spectrum of an adequately attenuated Thorium-Argon lamp will be recorded through the sky fiber during the object exposure. The `Object + Calibration` mode allows to record the first order residual motions of the spectrograph during the object exposure and allows to considerably improve the short-term radial-velocity accuracy. This technique in combination with software cross-correlation has successfully been used in the ELODIE instrument at the Observatoire de Haute-Provence and achieves an long-term accuracy of $< 15\,\mathrm{m/s}$ for a sharp-lined G dwarf.[7]
It should be noted here, that FEROS has originally not been designed for particularly high-precision radial-velocity measurements in the $1\,\mathrm{m\,s^{-1}}$ regime. Presumably, a dedicated design of an instrument for this purpose would be required. Anyway, the use of e.g. an iodine absorption cell placed in the telescope beam[8] to obtain higher radial-velocity accuracies of the order of $< 5\,\mathrm{m\,s^{-1}}$ could be evaluated in the future of FEROS.

3.2. The Instrument Calibration

For flatfield and wavelength calibrations, the calibration unit is equipped with internal calibration lamps which can be selected by remote control via a control box or the instrument control software. The UV-enhanced flatfield source uses two halogen lamps of different intensity and filter sets for shaping of the spectral appearance. The wavelength calibration source is a combination of a Thorium-Argon hollow-cathode lamp and an Neon spectral lamp, the latter replacing the wavelength range above 650 nm to eliminate the few strong red Argon lines which are about $70 - 100$ times stronger than the numerous Thorium lines used in the $370 - 650$ nm wavelength range of the spectrograph and usually contaminate the echelle orders by blooming on the CCD.

3.3. The Data-Reduction Software

A full on-line data-reduction system will be available at the telescope to enable the observer to fully exploit the capabilities of the instrument already during the observations. It is worth to note that because of the very stable spectral format of the bench-mounted and fiber-fed spectrograph, the correction for the blaze function that is needed to allow precise oder merging and continuum determination can be carried out with the internal flatfields alone. Further, cross-correlation facilities will be supplied for high-precision radial-velocity work and time-series analysis facilities for variable-star research which will presumably be the main fields of work for FEROS.

4. TIME SCHEDULE

The tight time schedule for the FEROS project is given in Table 2. It is planned to make the instrument available to the community in early 1999. The present status of the project is that the final design was presented to ESO at the design review at the end of June 1997 and was approved by ESO. At the beginning of the 1998 (February), most of the optical components are either already delivered to the consortium or close to their completition at the manufacturers. The mechanical components are in a comparable state.

Up-to-date information on the status of the project is available in the WWW on the FEROS homepage with the URL `http://www.lsw.uni-heidelberg.de/~akaufer/Feros.html`.

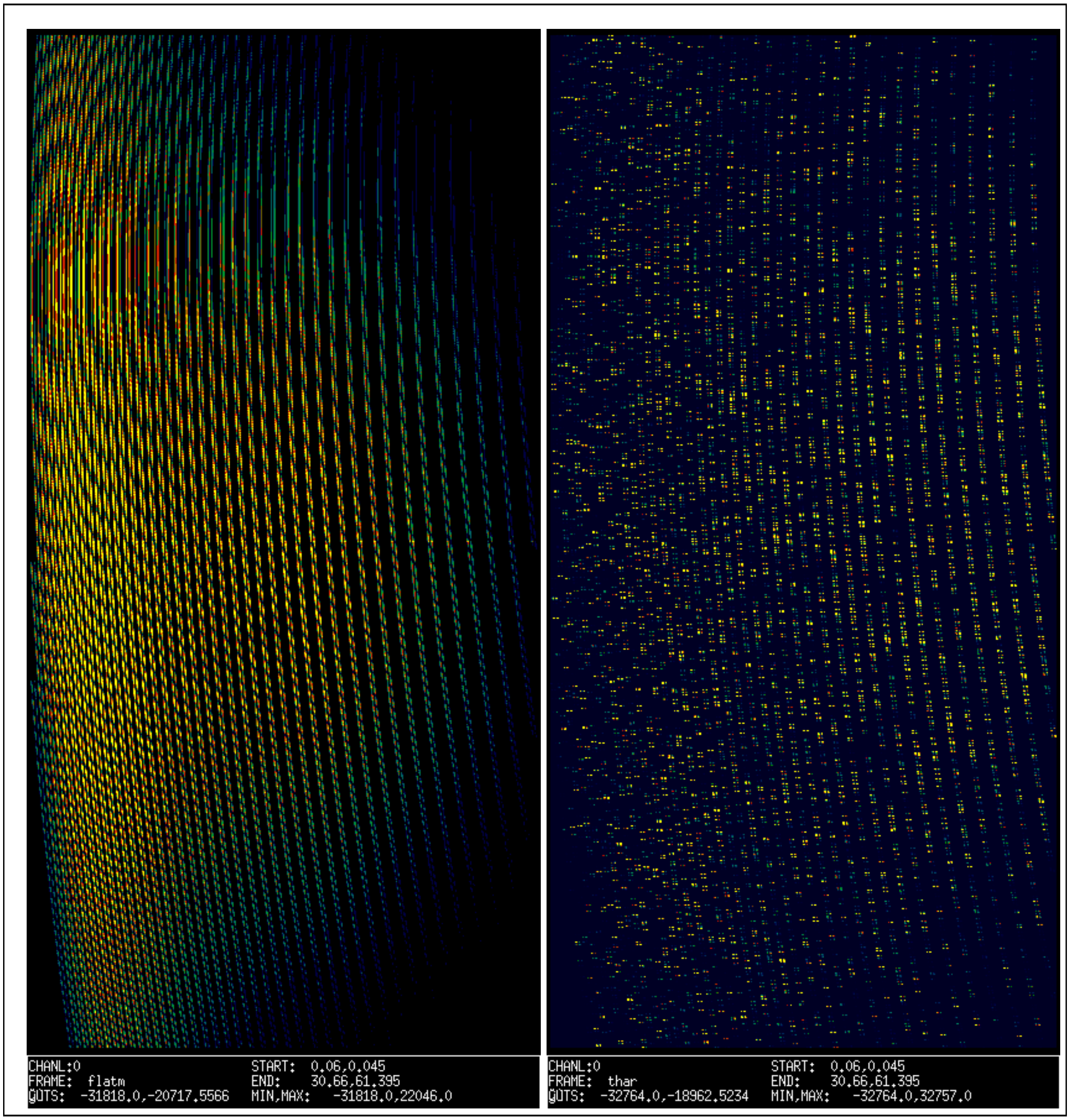

Figure 7. Simulation of the spectral format of FEROS for a flatfield exposure (left) and the corresponding Thorium-Argon-Neon calibration lamp (right). Red is to the left with the extreme order 32 with $\lambda_c = 985\,\mathrm{nm}$; blue is to the right with the extreme order 63 with $\lambda_c = 360\,\mathrm{nm}$. Each spectral order is double due to the illuminated object and sky fiber. The whole echelle spectrum is rotated counter-clockwise by 2.4° to align the slit image with the CCD rows.

5. PROJECT TEAMS

The project teams of the consortium and ESO consist of the institutes and the people listed in Table 3. The project is further supported by the technical advice of G. Avila, B. Delabre, H. Dekker, W. Eckert, A. Gilliotte, J.-L. Lizon, and R. Olivares at ESO.

Table 2. The time schedule for FEROS.

Contract Signature	September 1996
Final Design Review	June 1997
Integration	May 1998
Preliminary Acceptance (@LSW, Heidelberg)	July 1998
Provisional Acceptance (@ESO, La Silla)	December 1998
Availability to the Community	early 1999

Table 3. The FEROS consortium and the project teams.

Landessternwarte Heidelberg (LSW)
B. Wolf (PI), I.Appenzeller (Advisor)
A. Kaufer (Instrument Responsible)
W. Seifert (Optic Design), H. Mandel (Adjustment)
O. Stahl, A. Malina (Data-Reduction Software)
C. Hartlieb, L. Schäffner (Mechanics)
Astronomical Observatory Copenhagen (AOC)
J. Andersen, P. Nørregaard, J. Klougart (CCD controller)
Institut d'Astrophysique de Paris (IAP)
M. Dennefeld
Observatoire de Paris/Meudon (OPM)
R. Cayrel
ESO Garching
L. Pasquini (Instrument Scientist)

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