FIES: A high resolution FIber fed Echelle Spectrograph for NOT

Specifications and test results

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This document describes the specifications for the standby instrument FIES designed for the NOT. The design and construction was begun by the Nordic Telescope Group at Risø and later continued by B. Lindberg. Funding has mainly been provided by the VELUX foundation with a sum of 2.5 million Dkr. which was given to Prof. A. Reiz. He transfered the rights to the NOT organization, which has been responsible for the various contracts.

The design was already defined and described in a progress report published by NOTSA (Dybdal & Frandsen, 1992) and has not changed in any significant way since then. At that time the spectrograph was known as the VELUX instrument. This had to be changed as the name conflicted with copyrights of the VELUX company. Four small activity reports has been published since then over the period October 1995 to May 1997.

The philosophy behind the instrument is to build a stable, highly efficient, online spectrograph. The stability and the need for being online led to a fiber fed, bench mounted instrument. The optical table for the spectrograph is almost as large as it can be due to the limited space in the dome. The optical table makes it easy to modify the instrument according to the wishes of the nordic astronomers, and it can be seen as a kind of experimental platform, even if it is not foreseen to modify FIES very often.

The present report is supplemented by a technical report on the instrument written by B. Lindberg, which represents his final work under a contract with NOT.

1 Spectrograph specifications

FIES is a cross-dispersed (prism) Echelle spectrograph with a large format detector. The spectrograph is mounted on 600kg table with the size 1.25×3m. The light comes from a fiber assembly. The design is of the white pupil type similar to the design of FOCES (Munich, Cala Alto), HEROS/FEROS (Heidelberg, 1.5m ESO) and UVES (ESO, VLT). The optics permit two sources to be imaged on the detector simultaneously. One can observe target+sky or for bright objects target+reference or perhaps two target objects, if a proper fiber input is arranged.

The instrument consists of two units: the adaptor unit (or some other device for picking up light from the telescope, see details in a later section) and the spectrograph table. An additional utility is the calibration lamp unit, which provides a range of flatfielding or wavelength calibration sources. The calibration unit is coupled by optical fibers to the other units. It can be placed where it is convenient.

The specifications given below reflects the original assumptions about a standby instrument available within minutes at any time with a fiber adaptor unit picking out the light from the telescope beam. The adaptor is part of the telescope adaptor and light is directed towards the fibers by flipping a mirror.

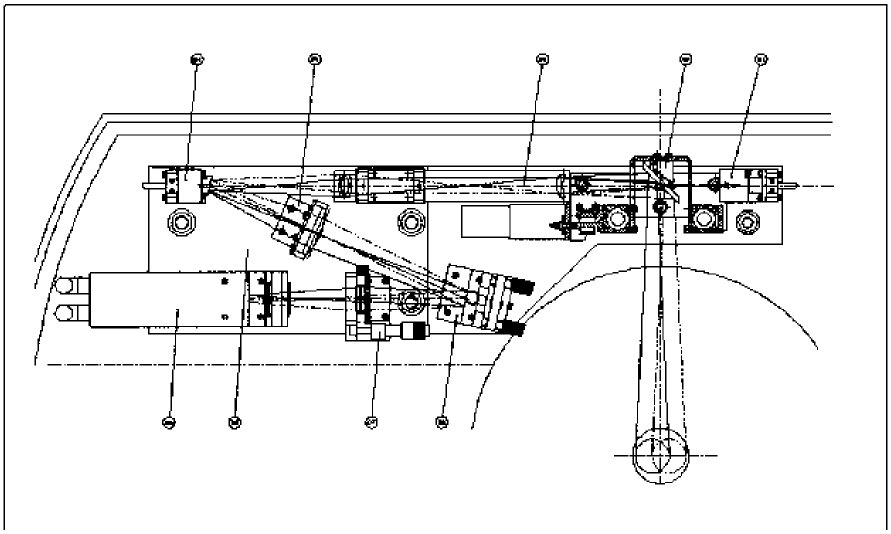

Figure 1: Drawing of the fiber adaptor unit (from Dybdal & Frandsen, 1992)

1.1 Fiber adaptor unit

This unit exists and has been tested in a first version. It should be emphasized that alternatives are being studied, which makes this unit obsolete (a fiber feed from the HiRAC II). Fig. 1 includes some of the following elements

- Optics to change the beam from F/11 to F/7.5 to reduce the effect of Focal Ratio Degradation (FRD). The fiber diameter is 100μm and imaged onto the sky represents 1.1 arcs.
- A set of rotating prisms to make Atmospheric Dispersion Correction (ADC). They are **not** seen on the drawing. The rotation must be controlled by the telescope control system (TCS). This has not been developed yet. It is not absolutely necessary, but will permit the spectrograph to work at all zenith distances.
- A movable folding mirror choosing between the sky and a reference light source (supplied from the lamp unit, see later)
- An intensified or low noise CCD camera for view the mirror with the fiber ends. Up to 10 fibers can be mounted in the present (existing) unit. Originally four fibers were envisioned: a blue and a red pair of target+sky fibers.

1.2 Spectrograph table

This year the spectrograph has been completed in the laboratory and first light achieved. Examples of spectra are shown later. The optics are schematically shown in Fig. 2 and a drawing in Fig. 3. The elements are:

- A fiber/slit unit with two sets of fibers and a mechanism to choose either of them (remote control). Furthermore a focal extender to match the f-ratio of the collimator changing F/6 to F/11. The slit width is adjustable (not under remote control). The fiber is imaged onto the slit with a diameter of 166μm, and the nominal slit width (at a resolution of R = 60,000) is 88μm. The slit then passes 67% of the light emitted by the fiber. (This whole unit is under reconsideration).

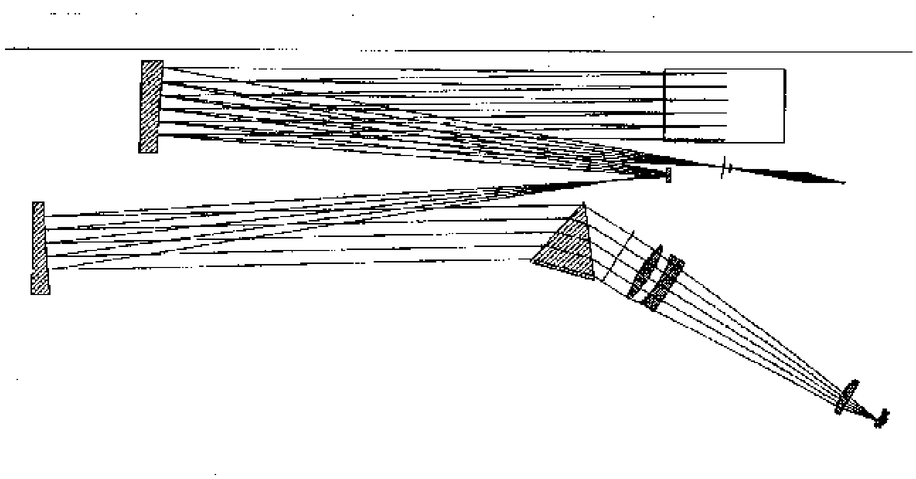

Figure 2: Schematics of the optics

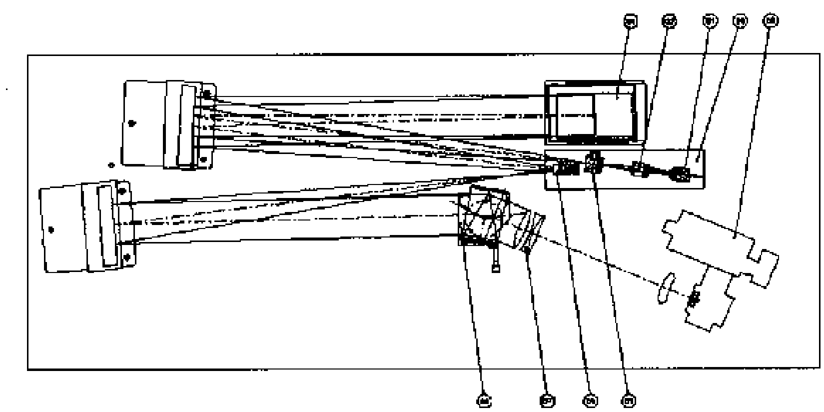

Figure 3: Layout of the optical table (from Dybdal & Frandsen, 1992)

- Two parabolic off-axis collimators, f=1524mm, D=250mm. The first one brings the light to the Echelle, which sends it back again. Then it is brought to a focal point, where a folding mirror reflects it to the second relay collimator.
- Echelle grating, 31.6 gr/mm, 63.5°, 154×306mm ruled area.
- Cross disperser, Prism of Schott LF5, wedge angle 48°, h=160mm.
- Camera, f=520mm, D=170mm, F/3.0
- Detector, Loral 2k×2k CCD with pixel size 15μm pixels. This chip suffers from the charge spread problem, and the effective resolution in the visual and blue part of the spectrum degrades to something of the order 30μm. The present chip is a reject that only works at almost room temperature. The vertical transfer fails when the temperature is lowered. A new chip is needed, preferably without the charge spread effect.

1.3 Lamp unit

To enable calibration procedures a lamp unit has been built. Five calibration sources can be installed and remotely selected by a moving mirror. They will also be turned on by remote control. Some sources have been installed like a halogen lamp for flat fields, a couple of spectral lamps. A Hollow-cathode Thorium-Argon lamp is being procured. The last lamp is needed for the final tests.

1.4 Theoretical performance

The resolution depends on wavelength through the aberrations in the system. Table 1 is a calculation from Dybdal & Frandsen (1992) that also tabulates the free spectral range for selected orders.

The spectral range covered is from 350nm to 820nm with a total efficiency including the telescope of the order 5-10% over most of the range. The format of the spectrum on the detector and a detailed discussion of the efficiency of the instrument is given in the technical report by B. Lindberg.

2 Tests of performance

2.1 Spectral resolution

The limited supply of light sources have made it difficult to measure the spectral resolution. Here we show the profile of two He emission lines at λ 5875.87 and 5875.63Å, i.e. $\Delta\lambda = 0.24$Å. The lines are clearly separated indicating that the resolution is not far from nominal. This is illustrated in Fig. 4 and Fig. 5. This is one of the first frames obtained and does not reflect the instrument perfectly aligned. If we assume the detector charge diffusion can be approximated by a Gaussian function with FWHM = 2 pixels (Andersen & Sørensen, 1997), then the resolution in this spectrum is somewhere in the range 45,000-50,000.

A more recent measurement is shown in Fig. 6, where two close solar lines in the range 6280 to 6310Å have been observed. The distance between the two spectral lines is 0.24Å and the width of the lines is according to a solar flux atlas 0.023Å. Measurements have been done with the nominal slit width and a narrow slit (not calibrated). With the narrow slit we reach a depth

Table 1: **Resolution and free spectral range for selected orders for FIES**

Order	Low Wavelength(Å) Resolution	Centre Wavelength(Å) Resolution	High Wavelength(Å) Resolution
69	8144 56700	8203 57700	8262 59100
84	6698 55900	6738 61000	6779 62300
99	5689 54000	5718 55500	5747 59500
114	4944 56400	4965 57900	4987 56500
129	4371 61000	4388 64100	4405 65100
144	3917 59800	3931 63500	3945 62000
159	3549 59400	3560 61300	3571 62600

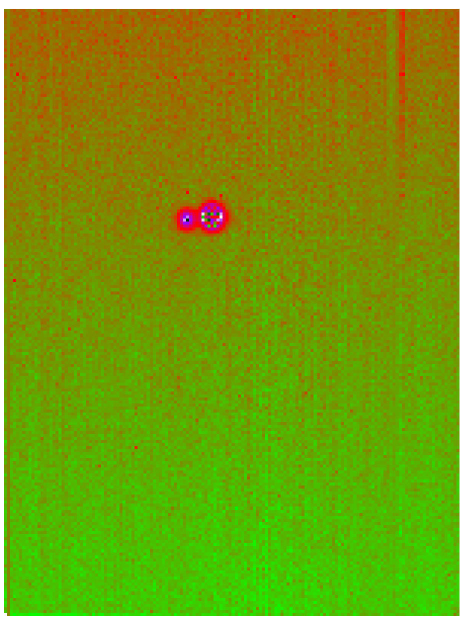

Figure 4: Small part of a CCD frame with the two Helium lines visible

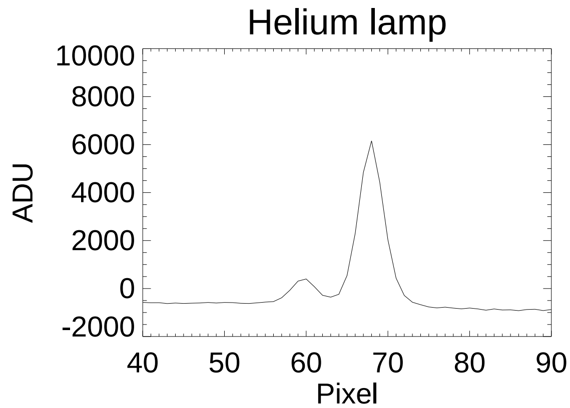

Figure 5: Scan of the rows with the Helium lines

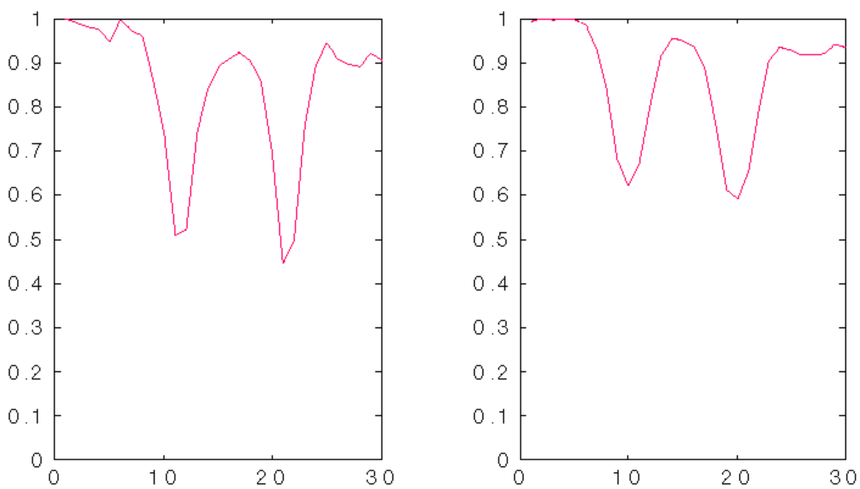

Figure 6: Solar spectrum, x-axis units are in pixels (0.024Åwide), y-axis the residual flux. Left figure is with a narrow slit (20–40μ, estimated value), the right with the nominal slit width 90μ.

in the line, wheich compares well with the solar atlas, which was produced with a resolution of R = 500,000. The detector used in this case has pixel size 8μm. By small adjustments of the optics it was possible to reach a resolution close to 60,000 with this detector. We conclude, that the optical aberrations are of the order expected and that the design goal of 60,000 can be reached with a CCD detector of 15μ pixel size. The tests are summarized in Table 2. For details see the technical report.

2.2 Throughput

The predicted efficiency of the whole instrument including the telescope optics is quite high. Depending on the setup (the fiber unit chosen, see later) for a given resolution, we find maximum values in the visible part of the spectrum between 10% up to as much as 30% at low resolution.

Some of the transmission properties have been measured in the lab and verified to match specifications. We have not been able to verify all the transmission values in the lab. Some

Table 2: **Resolution test summary**

Slit size	Specifications	Resolution of 0.023Å line	Res. of inf. narrow line
90μ	54,000-65,000	60,000	63,000
20–45μ	–	74,000	79,000

uncertainty still exists for the FRD of the fiber coupling, but we believe we are not far from correct values.

We refer to the diagrams in the technical report which give a detailed account of all the elements in the system for two different setups.

2.3 Stability

We have not had a chance to do tests that are relevant for the final instrument; we do not have an enclosure yet. A simple test was made, where the position of the Helium lines shown earlier were measured on exposures obtained on two subsequent days.

The shift in the line position was quite small, about 0.01 pixel which we think indicates that there are no strong temperature effects on the optical alignment.

3 Plan and budget for the installation at NOT

The spectrograph exists as a laboratory instrument. As no Coude room exists at the NOT, some work is needed before the instrument is ready to be mounted at the telescope. In this section the work to be done is described. The jobs can be divided in telescope dependent and spectrograph dependent parts. We will begin at the telescope end.

3.1 The fiber feed

The light from the target star entering the telescope need to be centered and focused on the fiber. Due to the large wavelength range of FIES a correction for atmospheric dispersion is needed to guarantee good performance for high airmass observations. The telescope F-ratio do not match the fiber very well and a focal reducer has to change the focal ratio to a smaller value like F/4 to F/6, smaller being better. Finally, a fast camera is needed to place the target star at the location of the fiber and to monitor the guiding. A second fiber is watching the sky at some distance from the target. This distance is yet to be determined.

There are several options for installing fibers at the NOT. They are discussed one by one.

3.1.1 A special adapter unit

A unit for feeding fibers has been constructed and tested on the telescope. This unit, however, is not complete and need some additional work. It needs a unit for correcting atmospheric dispersion (ADC), and the CCD camera for viewing the fiber ends need to be replaced by a more sensitive camera.

Both the ADC and the CCD camera are among the more expensive and time consuming parts needed, before the unit is ready to be mounted in the telescope adaptor. The ADC need

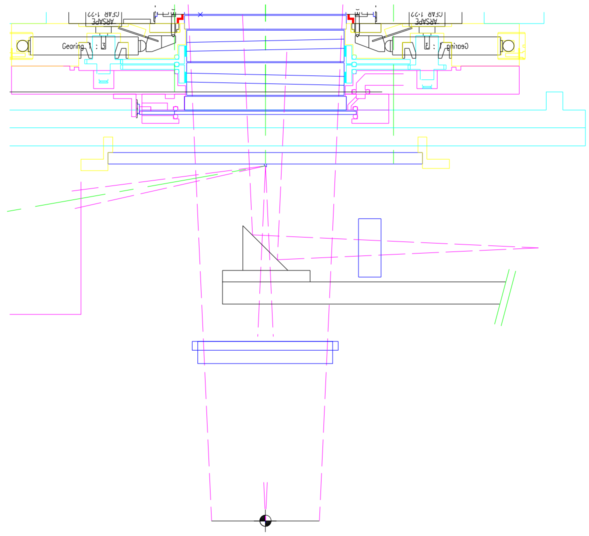

Figure 7: HiRAC II with a mirror and beamsplit (90/10) inserted

to be linked with the Telescope Control System that will supply the information necessary to control the prisms.

3.1.2 With HIRAC II

A very good solution would be to add the fiber feed to the HiRAC II adaptive optics system, which already includes the ADC and the viewing camera. A focal reducer is still needed and some sort of mirror to direct the light to the fibers. This option provides image stabilization, which means that the target is always nicely centered on the fiber. HiRAC II will in most cases be able to guide on the target itself.

This alternative saves the costs of a camera to monitor the position of the target on the fiber. It also utilizes the ADC that is part of HiRAC II, another important cost saving.

Some mechanical device is needed to insert a mirror in the telescope beam between the HiRAC II pickup plate (Andersen & Sørensen, 1998) and the filter or entrance window of the attached instrument (NOTCam or a direct CCD). A small fraction of the light must be returned to HiRAC II and the major part fed to a fiber by a focal reducer. An outline of such a fiber pickup is shown in a Fig. 7 provided by Michael Andersen/Niels Michaelsen.

If this solution is chosen, we also suggest that the fiber input to the spectrograph is organized in a different way than presently. Both a focal reducer and extender can be made very small. We propose to use fibers with total optical units included at both ends, which we call a fiber unit. Examples are shown in Figs. 8 and 9. One can then choose a fiber unit according to the observing program to obtain maximum efficiency. One can arrange to have several fiber units ready on a shelf, and it will be easy to change fiber unit. Also, fiber units can be prepared offline and installed at the telescope for specific purposes. This will make the modifications non-intrusive both at the telescope end and spectrograph end. This is a very large simplification.

3.1.3 With the standby camera

Alternatively a fiber fed can be arranged in the optical path to the standby CCD camera. This option has not been studied yet.

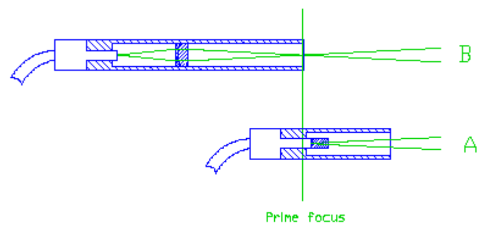

Figure 8: Input fiber unit models (from the technical report)

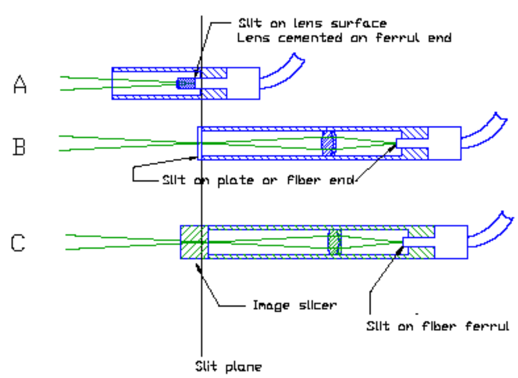

Figure 9: Output fiber unit models (from the technical report)

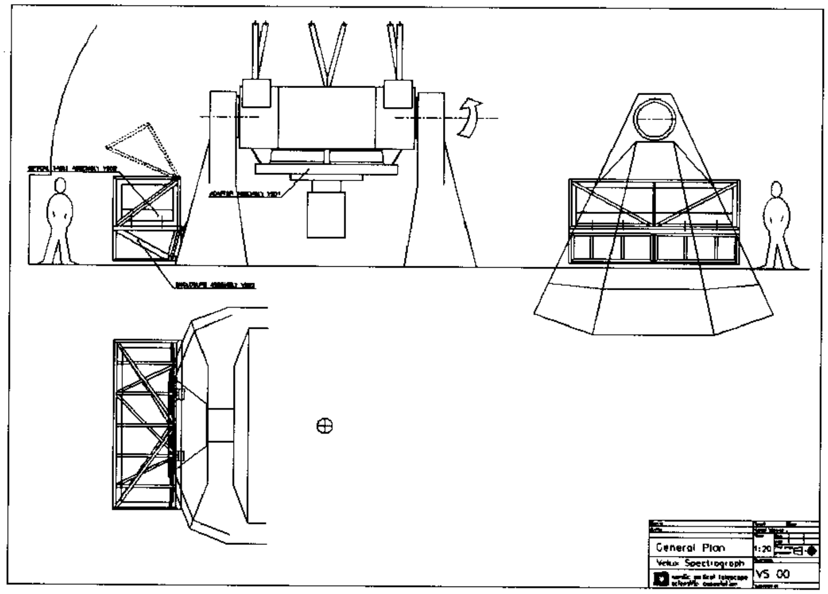

Figure 10: Placement of the optical table at NOT (from Dybdal & Frandsen, 1992)

3.2 Table platform

The only place at NOT to place the spectrograph in its enclosure is on the telescope itself. This has been studied before and some preparations started on the telescope. The figure from the early report by (Dybdal & Frandsen 1992) indicates where the table will be placed.

3.3 Fibers

The fibers leading the light to the instrument must be constructed with due respect to the cabling possibilities at the telescope. The length has an effect on focal ratio degradation and should not be longer than necessary. Excessive bending and changes of the fiber path during observations must be avoided. As described above we propose to use ready made fiber units, which include all input and output optics. It is possible even to include items like an exposure meter in such a unit.

3.4 Enclosure

The instrument must be operated at a constant temperature if the high stability is to be achieved. The observatory is from time to time in the midst of a cloud of very find sand from Sahara. The enclosure should provide protection against this dust. A thermal regulation and a small overpressure in the enclosure is planned to ensure stability and avoid dust accumulation in the instrument. The cooling of the detector is done with a Dewar with Nitrogen. Access to the Dewar and thermal insulation of the table against overflowing Nitrogen should also be arranged when constructing the enclosure.

The cooling system should at some later time be modified to a constant flow type system, which removes the need for Nitrogen refill. This will make operations easier and remove the thermal cycles introduced by Nitrogen refills.

3.5 Calibration lamp unit

Some spectral lamps are installed already, but we need yet to provide a lamp for precise wavelength calibration. A Thorium/Argon hollow cathode lamp will soon be provided. A complete system of electronic control of the existing power supplies and rotating mirror has to be constructed.

3.6 Remote operation

A small number of elements will be under remote control. Some of these elements are best integrated in the telescope system. These elements are all the movable mechanics in the fiber adaptor (if this unit is not rejected and replaced by feeding the fiber from HiRAC II).

The optical table only contains two movable items: a focus adjustment of the camera and a slide for choosing between two sets of fibers. These elements should be integrated in the instrument control system, which also should take care of the control of the lamp unit. We have looked on one option, where control is provided via a serial bus connected to a serial port.

3.7 Detector

A new CCD chip has to be purchased and tested. It should not suffer from the same degree of charge diffusion as the present test chip.

3.8 User's Manual

A users manual needs to be written. The manual should describe the instrument and the operating commands used when observing. It should also contain an introduction to a simple set of online reduction programs that permit the observer to monitor the quality of the observations.

3.9 Reduction software

The software for controling the instrument will be the BIAS program with a few additions. This program is wellknown by observers at NOT. Further data reduction can be done with IRAF, where a small set of prepared batch files will permit online reductions to take place during the observations.

3.10 Division of responsabilities

We suggest that the remaining work is divided between two groups in the sense that each group is responsible both technically and economically for the jobs allocated. Of course, the actual work can be subcontracted to institutes or companies, e.g. Bo Lindberg at LensTech AB.

The NOT group is given the job to procure telescope related items. *The spectrograph group* will complete the instrument and deliver items ready to be installed at the telescope. *The spectrograph group* will also be responsible for the operation of the instrument until it is fully tested. A negociation can then be held about a transfer of the instrument to *the NOT group*.

In practice a lot of collaboration is needed as decisions on one part easily has consequences for other parts of the instrument.

A proposed division of jobs is the following:

NOT group:

- Fiber adaptor unit and the electronics and control that goes with it. If the HiRAC II/FIES combination is accepted, this comes with the HiRAC II.
- Preparation of site.
- Installation of instrument (done together with the other group)

and

Spectrograph group:

- Enclosure and temperature control
- Fiber unit(s), (NOT specifies length)
- Remote control of optical units on the table and the lamp unit.
- Instrument software including simple reduction package
- A users manual
- Final laboratory tests
- Detector
- Installation of instrument (done together with the other group)
- Operations during a first two? year period

3.11 Budget

This section ends with a budget for the costs of the implementation at the telescope. It has been assumed that Bo Lindberg will be in charge of the completion of the spectrograph. Most of the electronics and the software will be provided by the Institute of Physics and Astronomy, Aarhus University. There are no assumptions made about the sharing of the costs. NOT could decide to finance the completion or national funding might be attempted. It should be pointed out, though, that NOT formally is the owner of the instrument as Prof. Reiz has handed over the rights to NOT. Table 3 is a summary of the costs for the different parts.

4 Future upgrade

We suggest that FIES is completed more or less as specified the only exception being the fiber feed unit. But it is evident that there are many possibilities for upgrading the instrument. A suggested upgrade plan can be described by the following sequence of improvements:

1. Image slicer (FEROS/ESO type) combined with modified slit assembly to increase efficiency by minimizing Focal Ratio Degradation (FRD). This will be needed for the upgrade to higher resolution. The image slicer would be part of a fiber unit and will not imply further modifications of HiRAC II.

Table 3: **Completion costs for FIES**

Component	Cost(in thousand SEK)	Comment
FRD and fiber construction	90	LensTech
Adaptor	100	To complete the existing unit but not needed if integrated with HiRAC II
New CCD chip	?	Depends on availability
Computer control	40	Aarhus?
Support/Enclosure	50	LensTech/NOT?
Transport/Assembly	110	LensTech/NOT?
Total	290 + adaptor + CCD chip	Depends on technical solution

2. A reference light arrangement, where continuum light is passed through an iodine cell and then inserted through a fiber into the telescope beam in such a way that it follows the same optical path through the spectrograph. By shifting the pixels 10 pixels up and down as the reference light is on or off, one obtains two spectra on each CCD frame, one from the target object (the star) and one from the reference source. One must ensure that one gets the same optical path through the instrument for the reference source and the target. It is of course also possible just to insert an iodine cell in the normal target beam. Again this is a special case of a fiber unit, that is external to HiRAC II and the spectrograph.

3. Upgrade to resolution R=120,000. In order to achieve a higher resolution without sacrificing efficiency the following modifications are necessary: a new CCD camera with a 2k$\times$4k or 4k$\times$4k chip, a new longer focal length camera, a modified cross disperser prism which at the same time produces more evenly space orders and correction for optical aberrations. Two silica plates are added to the prism as windows and fluid quarts filled in the space between the windows and the LF5 prism. A thin silica corrector plate is added to this assembly. A calculation by M. Andersen shows that a spacing varying between 21 to 30 pixels can be obtained for the order spacing over the whole spectral range.

4. Addition of an (optional) double pass mode, which reduces stray light significantly and increases resolution further to as much as 200,000. This is at the cost of loosing part of the spectrum on the detector.

The first upgrade is not very complicated as a copy of existing image slicer devices produced at ESO can be used. The cost should not be excessive either. The second is simple, but will demand some modifications of the fiber feed. The third and fourth are major upgrades, which are relatively expensive. The main cost will be the detector costs. The main work is in the design and manufacturing of the camera and the modification of the prism.

5 Operation at NOT

We suggest that FIES operates similar to SOFIN in the beginning until operations has stabilized. It is made available for a given block of time. In the beginning of that period one or more members of the spectrograph group will be present and ensure proper functioning of the instrument. It then stays on and can be used by observers for the rest of the period agreed on. In case of instrument failures it is the spectrograph group that takes action to fix the problems.

6 Recommendations

Whether interest has been expressed in using FIES or not, several research programs exist in the Nordic countries, which would benefit from the presence of FIES at the NOT. Examples are Doppler imaging, abundance studies and spectral variability in non-radial oscillating stars. The instrument is very efficient and very stable and can be upgraded without too much difficulty to a resolution as high as needed by any of the research groups. It will be available at the telescope a large fraction of the time with very short notice (when HiRAC II is mounted).

We therefore recommend that the instrument is installed at the telescope. The best solution is in our opinion to combine FIES and HiRAC II and to complete the instrument as described above. Almost all the work will take place in *the Spectrograph group*.

After a trial period the performance of this instrument can be compared with SOFIN or other alternatives and a decision be made whether the instrument should become a core instrument. A decision on any upgrades to make it a really unique facility could be made at the same time.

Both this report and the technical report by Bo Lindberg can be downloaded by anonymous ftp as a postscript and portable data format (.pdf) file respectively from `obs.aau.dk:/pub/srf` as the files `STC_report.ps` and `fibidea0.pdf`.

References

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