The FIES SPECTROGRAPH for NOT

Results from lab. tests, and some new ideas

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CONTENT

1 INTRODUCTION

The FIES spectrograph is now in existence and works in the laboratory. The details of the work that is left do is described in the attached report. Here, new estimates of the fiber transmission is done, and results from resolution tests is presented. Also, some new ideas of how to make the instrument more flexible, and more stable, is described. In addition, we discuss the problem of upgrading the instrument to R>100.000.

2 TRANSMISSION OF THE FIES SPECTROGRAPH

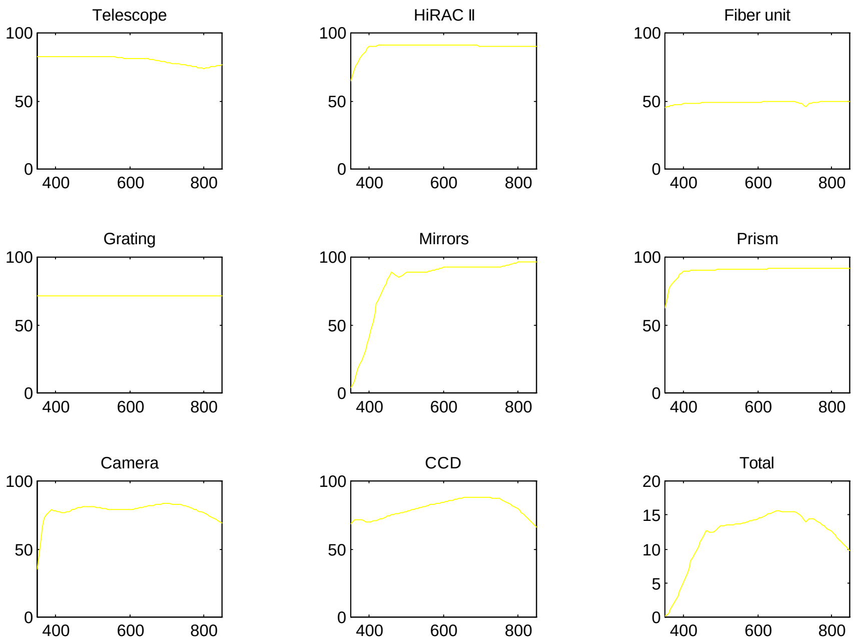
The transmission values of the spectrograph has been estimated as described in the table below. The left column lists the different degrading effects. The sign (----), means that the effect is left out. Coating and absorption curves have been stored in a Matlab program that calculates the nine graphs that shows the transmission characteristics. A few different alternatives have been calculated. One transmission measurement has been done with a He-Ne laser. The chain: Grating +Mirrors + Prism + Camera was proved to have close to the predicted throughput.

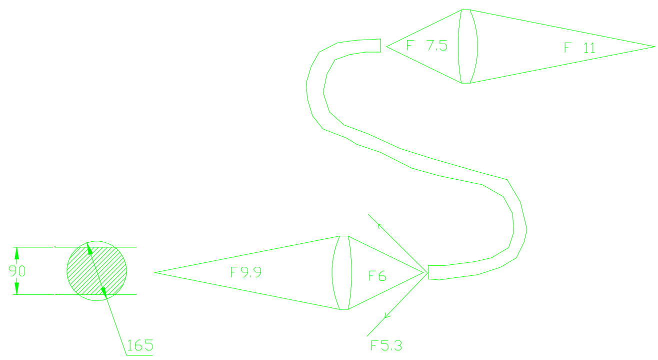
It is assumed here that the fiber unit is built according to the AA alternative (see *new ideas* below). There is some guessing in the FRD values. They are based on extrapolations from a few simple measurements on the fiber. Before the final fiber is built, better measurements must be done on the fiber cut to the length that it will have in the instrument. It is assumed that the light is coupled into the fiber from the HiRAC II (see the attached report). Since HiRAC II has a very high throughput, we gain a lot by doing that.

	No. of surfaces	*Transmission*
Telescope		
Absorption of pure (fresh) aluminum	2	Pure Aluminum
HiRAC II		
Corrector package		0.94 (From HiRAC spec.)
Pickup plate	2	0.992*0.992 (Super Triolin)
45 degree mirror	1	Silflex or Aluflex
WFS		-----
Fiber unit		
Seeing effects		----
Absorption reducer glass		----
Reflection reducer	1	0.992 (Super Triolin)
Absorption fiber		Absorption curve
FRD fiber		Depends on fiber unit
Vinjetting slit		Depends on fiber unit
Absorption extender		----
Reflection extender	1	0.992 (Super Triolin)
Grating		
Vinjetting by grating		0.95
Efficiency of grating (At center of the orders)	1	0.75
Spectrograph mirrors		
Absorption of mirrors	4	Protected silver / Silflex / Aluflex
Prism		
Absorption of glass in prism		Absorption curve of LF5
Reflection loss (uncoated surfaces)	2	0.96*0.96
Camera lens		
Absorption of five lenses		Absorption curves of glasses
Reflection loss (front lens)(now uncoated)	2	0.96*0.96
Reflection loss (the other lenses)	8	Coating curves
CCD		
Reflection loss from vacuum window	2	Coating curve
Absorption vacuum window		----
CCD quantum efficiency		QA curve

Present design

The graphs below shows the transmission of the present spectrograph. The fiber is not built yet, but it is assumed that it is made to give the specified resolution (60.000). The mirror coatings are protected silver, that has a poor quality around 400 nm, compared to Balzers Silflex coating, that exists now. Below 400 nm silver coatings perform very badly. Balzers says that they can not even predict what is going to happen below 400 nm. If good transmission below 400 nm is important, we have to change to Balzers AlflexUV coating, or something comparable. Even if we chose silver it is a good idea to change to Balzers Silfex, instead of the one we have now. The parameters of the fiber unit is shown by the conceptual drawing below the curves (see *new ideas* below).



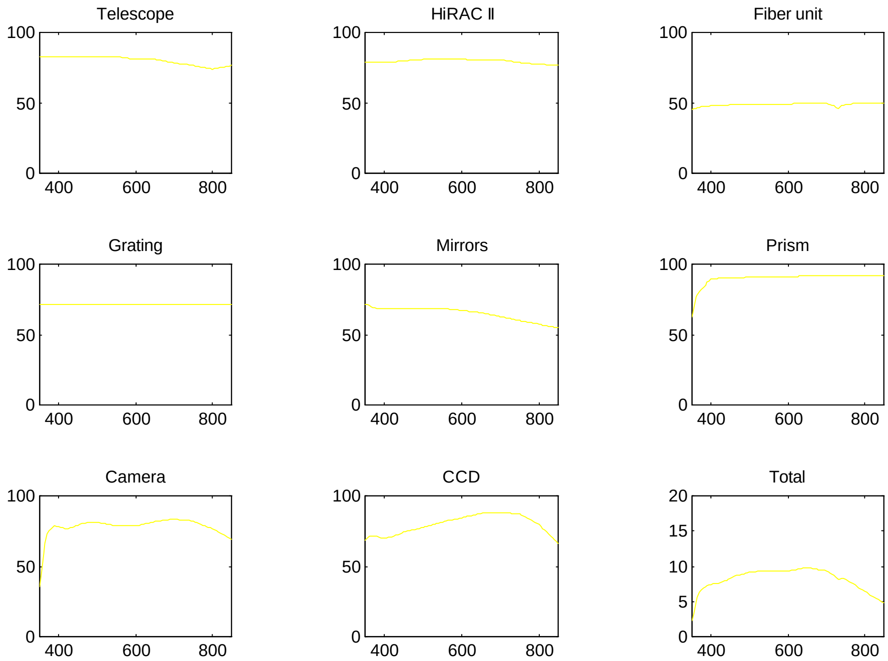


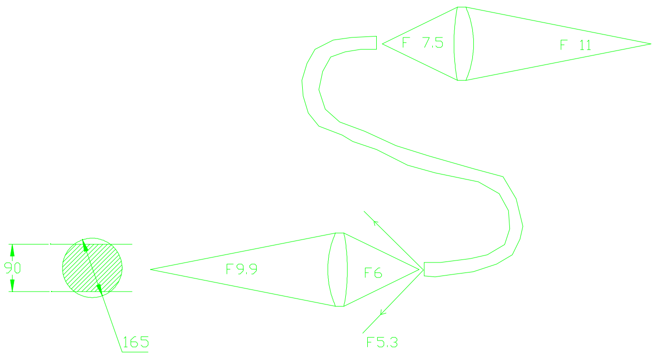
Fiber length	4.6 meters
Fiber diameter	100 m
Slit size	90 m
Image slicer	---
Nominal resolution	**69500**

FRD	0.78
SLIT VINJETTING	0.65
FRD + SLIT VINJETTING	**0.51**

Present design with Aluminum coating on mirrors

Since the UV-part of the spectrum is important for this instrument, we probably have to change the mirror coating to aluminum. The transmission data with Balzers AluflexUV on the mirrors is shown below.



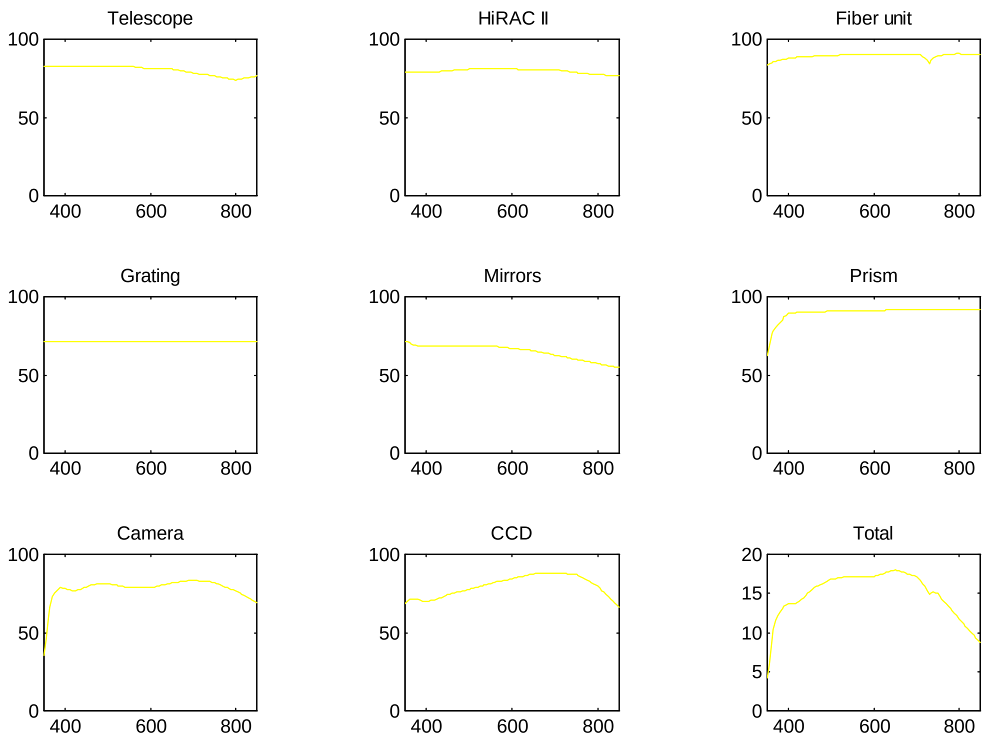


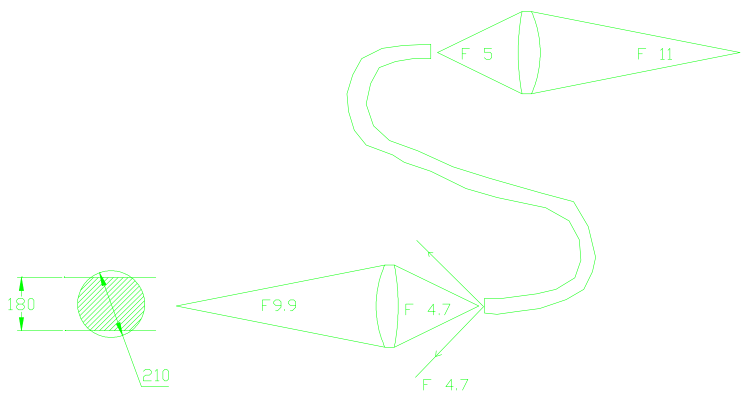
Fiber length	4.6 meters
Fiber diameter	100 m
Slit size	90 m
Image slicer	---
Nominal resolution	**69500**

FRD	0.78
SLIT VINJETTING	0.65
FRD + SLIT VINJETTING	**0.51**

Maximum transmission design

In this case we use an other fiber unit. The focal extender and slit is changed to give maximum transmission. The price is paid with lower resolution (30.000). The mirror coatings are aluminum (Balzers AlflexUV). We can raise the resolution up to 60.000 again if we use an image slicer (2x). This will probably cost 10% of the light. (The number is picked from the FEROS documentation)





Fiber length	4.6 meters
Fiber diameter	100 m
Slit size	180 m
Image slicer	---
Nominal resolution	**34750**

FRD	1.0
SLIT VINJETTING	0.93
FRD + SLIT VINJETTING	**0.93**

3 RESOLUTION TESTS

Resolution test on lines in the solar spectrum

A fair test of the resolution of the spectrograph should be to observe lines in the solar spectrum. This is close to how the instrument will be used in practice, and stray light levels are more realistic, than if spectral lamps are used.

There are a some rather sharp atmospheric absorption lines in the solar spectrum between 6280 and 6310 Angstroms (see Echelle spectrum format in the appendix). The test was carried out with the bare fiber aimed at the sun, early in the afternoon. One line pair was observed and the profile were recorded. The result is shown in Fig. 1 and Fig. 2.

The curves are normalized. The units along the x-axis is pixels, and the pixel size is 8 microns. The distance between the two peaks is 10 pixels (Equal to 80 microns or Δl =0.24 Angstrom). The width of the lines were according to a solar atlas 0.023 Angstroms, approximately a tenth of the distance between them. The profile in Fig. 1 was obtained with a small slit size (20-45 microns, the value was not recorded), and the profile in Fig. 2 was obtained with a slit size of 90 microns, which is the size specified for FIES.

To calculate the linewidths, gaussian functions have been fitted to the profiles in a least squares sense, and the width has been taken to be that of the fitted gaussian. The average linewidth of the two lines in Fig. 1 was found to be 2.99 pixels, and the average in Fig. 2 was 3.66 pixels.

To obtain the instrument profile, the influence of the lines own width must be eliminated. This is done by a deconvolution, which is easy if we assume that the intrinsic line profile is also a gaussian. The following formula was used:

$$w^2_{INSTRUMENT} = w^2_{MEASURED} - w^2_{INTRINSIC}$$

It turns out that the intrinsic linewidth have an almost negligible influence. The instrument profiles was found to be 2.82 and 3.52 pixels, for the two slit sizes.

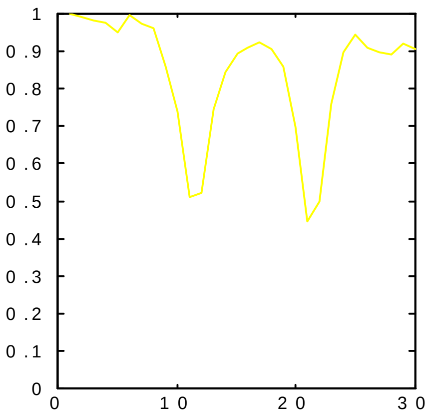


Fig. 1

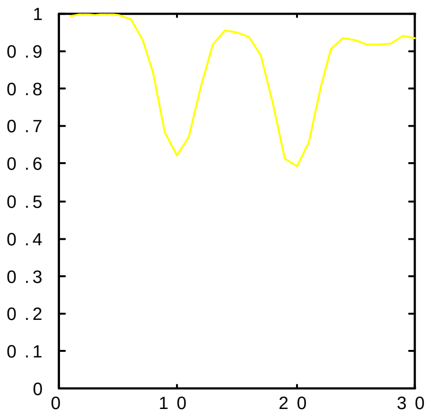
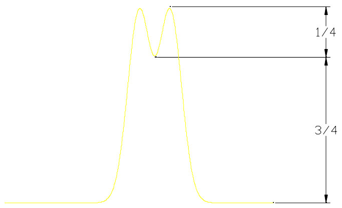


Fig. 2

To calculate the resolution of the instrument, we require that the dip between two resolved lines must be at least one quarter of the height. See the figure below.



For lines with a gaussian profile, this has the consequence that the distance between the lines must be 1.17 times the linewidth, at the resolution limit. If we use this rule on the numbers above, we get a resolution of 79.000 with the narrow slit, and 63.000 with the 90 micron slit. The specified value with a 90 micron slit lies between 54.000 and 65.000, depending on wavelength, so the main conclusion here is that the specification is fulfilled. As long as we have a pixel size of 15 micron on the detector, we will of course never obtain resolutions over 65.000 or so.

According to theoretical aberration curves, it should be possible to observe a higher resolution than 79.000 (with the test camera and slit smaller than 90 microns). This could indicate that there still is alignment errors in the system.

An other line pair (also in the red end of the spectrum) was observed. The distance between the lines were 6 pixels (Equal to 48 microns or $\Delta\lambda$ =0.14 Angstroms). They were well resolved with a slit size of 90 microns, and very well with a slit size of 45 microns. The linewidth of these lines are not known, but one of them appeared to be broader than the lines in Fig. 1 and 2.

In the blue end of the spectrum, the lines seems to be broader in general, so no good test lines were found, but from a visual judgment there seems to be no big variation in resolution over the field. Between 4549 and 4550 Angstroms, there are four lines, broader than the red lines observed, that lies on top of a broader absorption band. They have a low contrast, and the distance between the closest ones are 9 pixels (Equal to 72 microns or $\Delta\lambda$ =0.15 Angstroms). These lines could be resolved when the sun was low, but not with such a good contrast as in Fig. 1 and 2. When the sun was higher, early in the afternoon, one could see that there was something, but it was not possible to count the lines.

Resolution test on lines from a spectral lamp

The line profile was also tested with a line from a Helium lamp (Fig. 3 and Fig. 4). The two curves of Fig. 3 was obtained with the slit sizes 90 microns, and 30 microns. The curve in Fig. 4 was made with the slit fully open. The effective slit size is then the same as the fiber diameter in the slit plane (165 microns).

Since the profiles are broader than the profiles taken on the solar spectrum lines, the conclusion was drawn that the lines are to broad to give a good test of the instrument profile. In addition, it has been impossible to get information about the linewidth of these lamps.

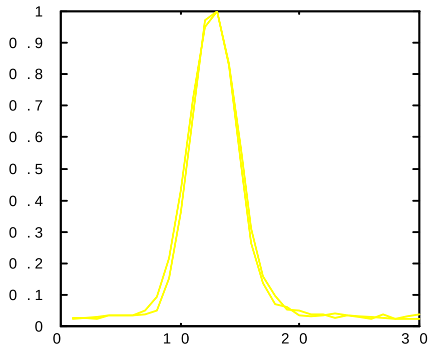


Fig. 3

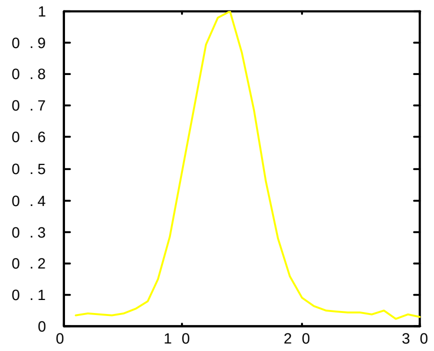


Fig. 4

Order separation

Fig. 5 shows a profile across the orders in the spectrogram. The units along the x-axis is in pixels (8 micron size). The profile was taken with both the object and the background fibers illuminated with white light. The lower peaks could for ex. be the background orders.

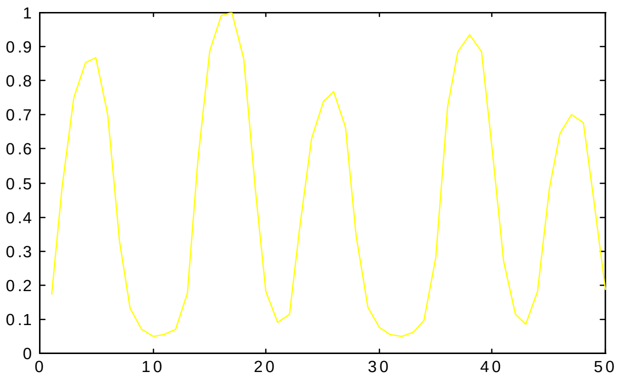
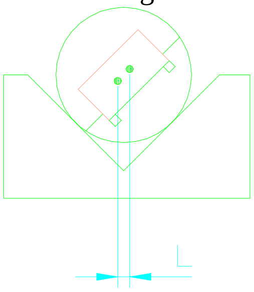


Fig. 5

An other resolution test

An simple experiment was carried out to test the resolution of the optical system of the spectrograph, without the use of a spectral line. The focal extender and slit was taken away, and the fiber pair (both illuminated) was moved to the slit plane. By rotating the ferule the horizontal distance between the object and background fibers could be varied (L in the figure below). The idea was to pretend that the object order, and sky order represented two wavelengths that was to be resolved.



This way, we could rotate the ferule until the orders was not resolved anymore, and estimate the resolution from the distance between the fibers. The size of the fiber is 100 m ,so it is not such a bad simulation of the real 90 m slit.

Of course, the direction on the detector is wrong. We measured at right angles to the dispersion direction. The experiment was easy to do, so we thought it was worth doing it. The problem with measuring the spectral resolution is that it is hard to find lines of equal strength at the right closeness for a good test. This measurement should bee seen as a complement to the estimation of resolution from linewidth measurements on spectral lines. The pixel size of the camera was 11 m in this direction.

Since this test was carried out a better adjustment of the spectrograph has been found, so the contrast of the profiles should be better than shown here.

Simulated l / Δl	L	L(on detector)	
50.000	121 m	41 m	Fig. 6
55.000	110 m	38 m	Fig. 7
57.500	105 m	36 m	Fig. 8
60.000	101 m	34 m	Fig. 9

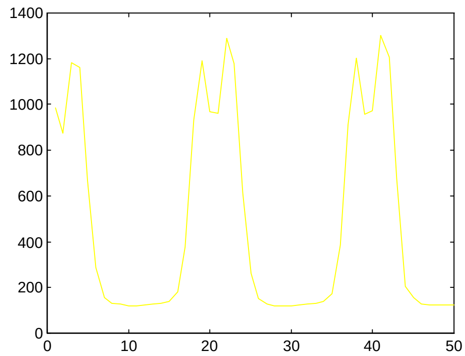


Fig. 6

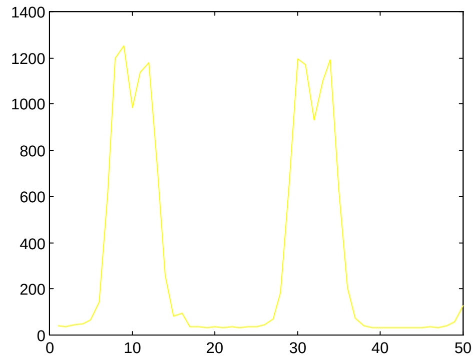
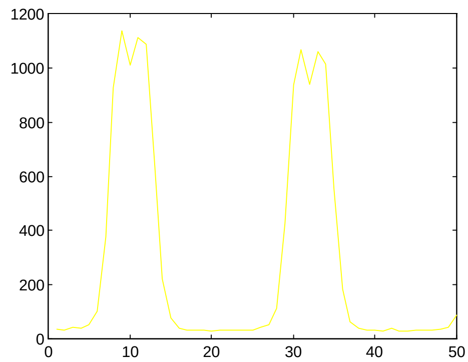


Fig. 7



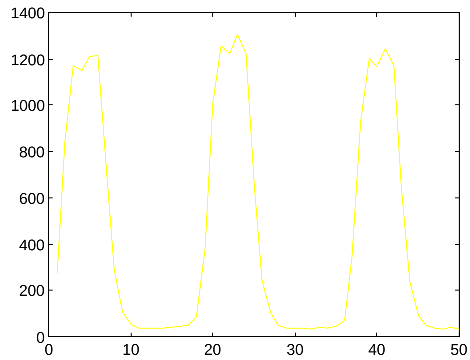


Fig. 8 Fig. 9

4 NEW IDEAS

The fiber unit

The basic idea presented here is to build the combination Focal reducer + Fiber + Focal extender + Slit + (Image slicer) into one ”fiber unit” that can be connected or disconnected from the spectrograph and telescope very easy. The whole unit should be outside the spectrograph enclosure, telescope adapter, or HiRAC II camera (In this discussion it is assumed that the light is coupled to the FIES fiber from the HiRAC II).

This way, we could reconfigure the spectrograph within minutes. It could be used for high resolution, or high throughput, single fiber, double fiber, different fiber distances in the double case, and so on. This would make the spectrograph very flexible. Some projects could even have its own fiber. Also, all upgrading work on fiber units can be done at home, with no disturbance at the telescope.

There is one company on the market today, that can make a multi-fiber for $200. The design is the same as the one we have invented for the FIES fiber. In the integrated end the fibers are lying in V-grooves in a silicon plate, and the loose ends can have standard connectors. It can take up to 32, or so, fibers. The customer can choose fibers, and the distance between the fibers. So, the multi-fiber itself can be a cheap off the shelf product. Of course, the other parts of the fiber unit have to be built by ourselves.

Figure 10 depicts the general idea, figure 11 shows conceptual drawings of two possible input ends, and figure 12 shows three possible output ends.

The focal reducer and extender can be made much smaller then they are today. This would give a better stability. The holders for the fiber at the spectrograph and telescope, can be simple V-blocks, with a high repeatability. It we exchange the whole present input mechanics against a V-block, we get a great simplification and probably a higher stability. If we want it that simple, we have to through out the fiber shift mechanism also, which might be negative. On the other hand a fiber exchange should be very simple. Also, the argument for the fiber shift unit was that there was a need for a blue and a red fiber. There are new fibers in existence today, that might make the red fiber unnecessary.

One very simple fiber unit would be the A-A alternative. If the small lenses are cemented on the ferule ends, the whole unit would have only one input surface, and one output surface, and thereby high transmission. We could have single or double fibers. The slit can be coated directly on the ferule end. That should not be to complicated. A wire could be used as a mask over the fiber during the coating process.

With the slit on the ferule, we can have slit and image slicer at the same time. An image slicer should be possible to integrate into the output end of the fiber unit, or it can be placed in the V-grove holder in front of the fiber output, when needed, as a loose component. However, it have to be very well centered in a cylindrical holder. The shutter, and other components, for ex. a photometer, can also be placed in the V-groove. If the V-block are aligned relative to the spectrometer one and for all, there is no need for a new alignment if components in the V-block are exchanged. The only moving part inside the spectrograph would be camera focus.

The V-block at the HiRAC II end could have place for the reference fiber input, and maybe an iodine cell input as well. The only FIES components needed inside the HiRAC II is a 45 degree mirror, and a beamsplitter to take off some light to the WFS, if we need that. This concept makes it possible to work on the whole chain of components in a very non-intrusive way for the telescope. In addition, the only FIES component that have to be controlled by the telescope control system is the 45 degree mirror, so from the telescopes point of view there is almost no difference between a FIES observation and a HiRAC II observation.

However, to make this concept practical we need to have access the telescope focal plane outside the HiRAC II wall.

Last of all, the final fiber is not built yet, so we can do this from the beginning on the present instrument.

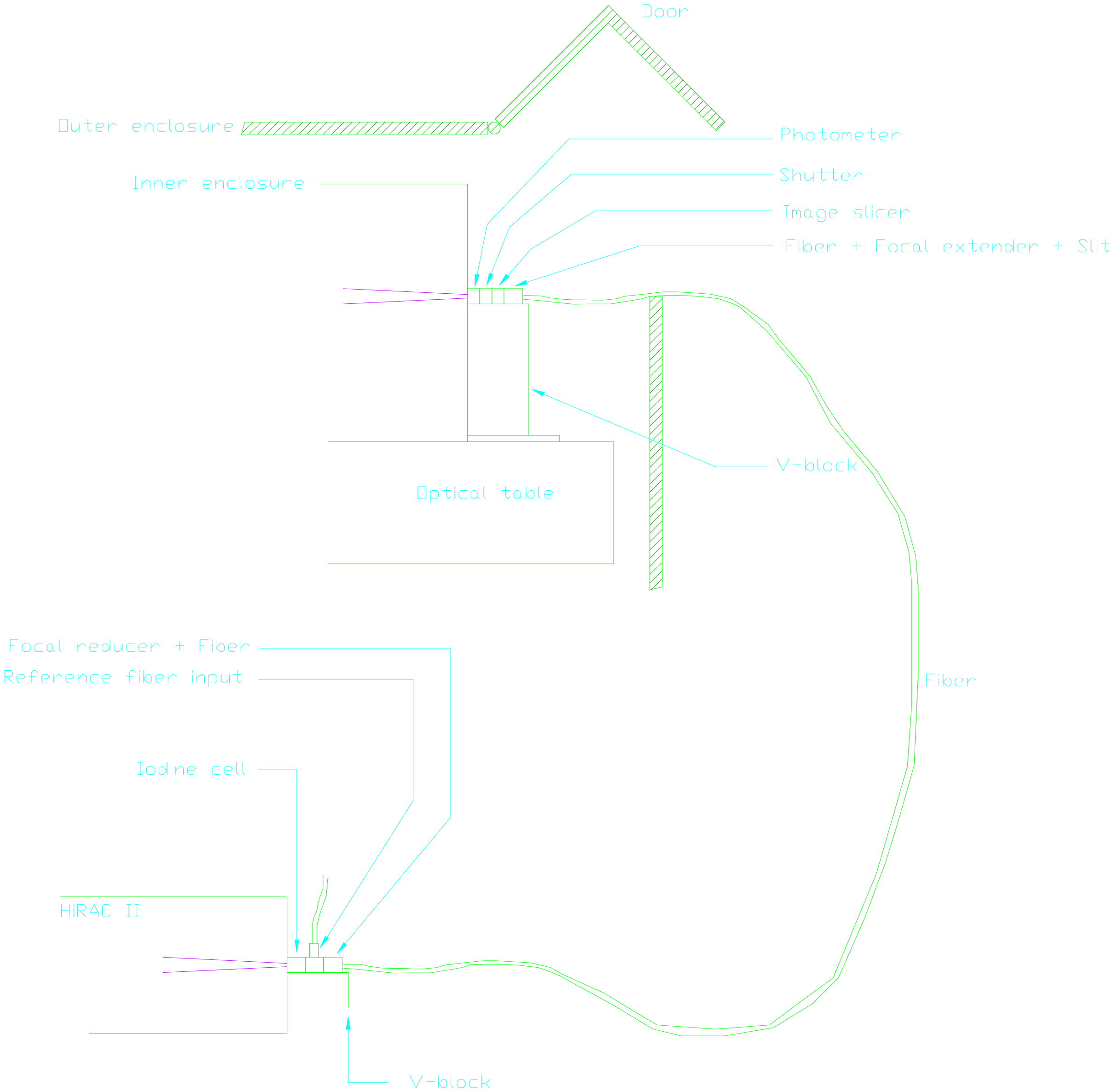


Fig. 10

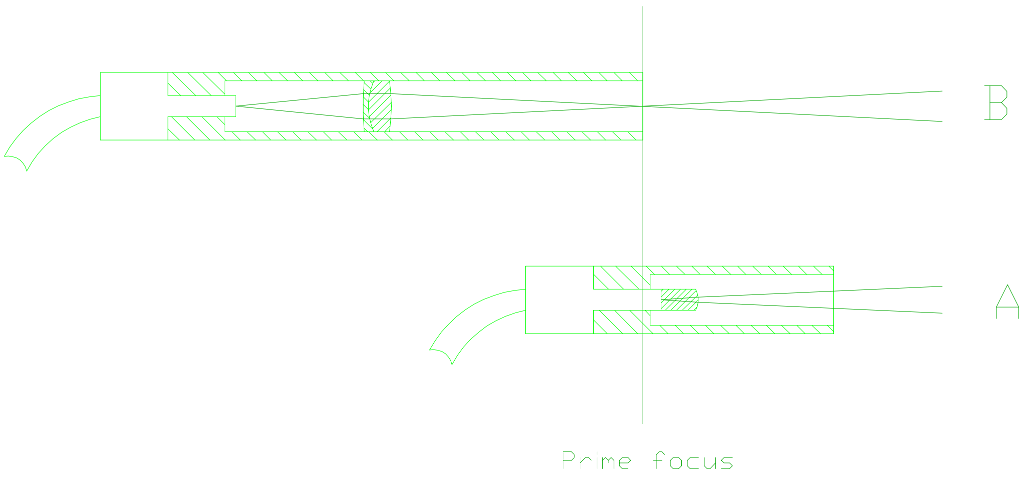


Fig. 11 Input end

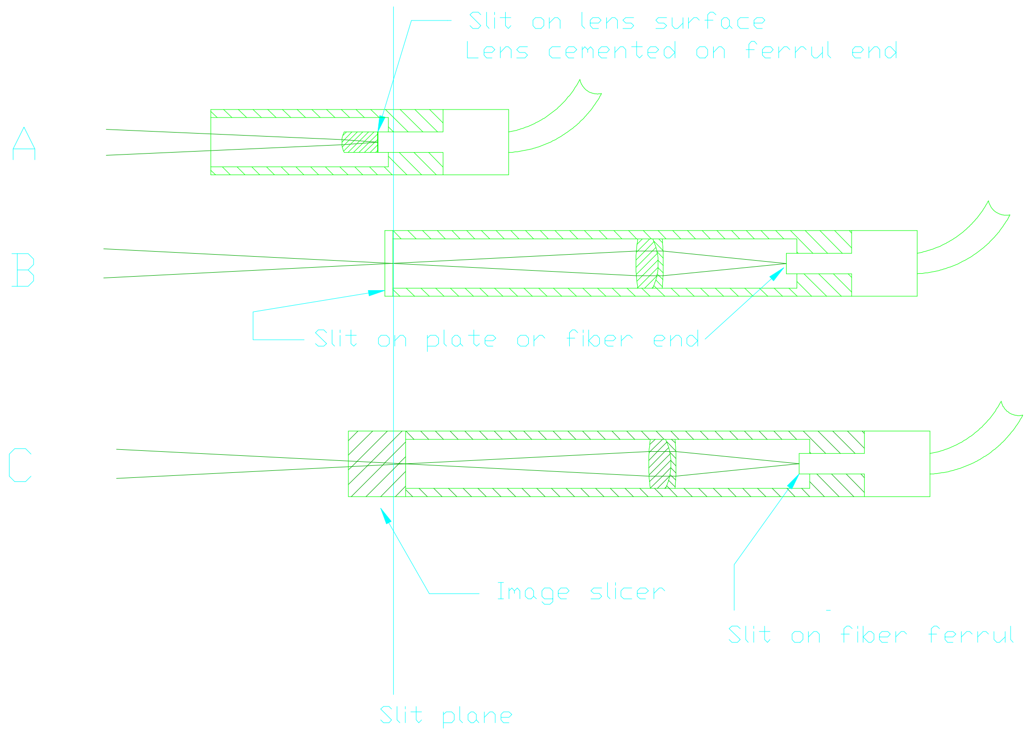


Fig. 12 Output end

Doubling the resolution to R=120.000

To double the resolution of the spectrograph, the sampling at the detector has to be doubled. This can be achieved with a new camera lens, with a focal length of 1000 mm, and a 4kx4k detector. In addition, the slit size has to be decreased to 45 microns. This can be achieved with an image slicer.

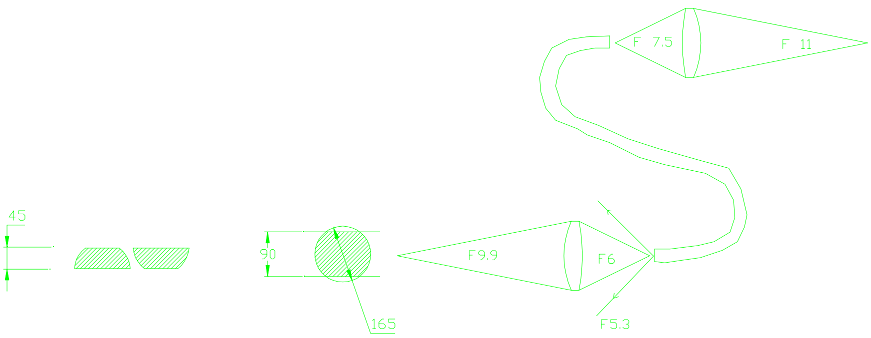
The aberrations of the total new system must not be higher than in the present system. Slightly lower aberrations would be desirable. The whole optical design problems lies in the camera lens. The rest of the system has, theoretically, zero aberrations, except for a cylindrical image curvature, that can be corrected with a cylindrical lens.

The design problem of the camera lens is mainly one of correcting the chromatic aberrations. This problems get worse with longer focal lengths. The monochromatic aberrations will probably be easier to correct in the F6 / 1000 mm lens than in the present F3 / 520 mm lens. An attempt to design a new lens was made by scaling the old lens to 1000 mm, and reoptimize it for F=6. The result was a lens with similar performance as the old one.

A new technology that could result in a better and at the same time cheaper lens would be to use liquid lenses. Lookheed in Palo Alto seems to have pioneered this area, and in articles they claim that the use of optical liquids can reduce the cost of an apochromatic telescope lens with a factor between 3 and 10. At the same time the liquids results in better color correction. On the negative side, is sealing problems, and temperature coefficients about a hundred times that of glass.

Since the environment will be very stable for this lens, there is a chance that this technology could be an opening to a rather cheap upgrade of the spectrograph.

To get an idea of what the transmission of an instrument with R=120.000 would be, we could just add an image slicer to the model ”Present design with aluminum mirrors”. It would lower the total with maybe 10%. The fiber unit would be as shown below. The input F number to the fiber could be questioned here, but measurements on fibers with the final length are needed to find out if it to optimistic.



Fiber length	4.6 meters
Fiber diameter	100 m
Slit size	90 m
Image slicer	2x
Nominal resolution	**139.000**

FRD	0.78
SLIT VINJETTING	0.65
IMAGE SLICER	0.90
FRD + SLIT + SLICER	**0.46**

APPENDIX Echelle spectrum format

The figure below shows the Echelle spectrum format. The inner square represents the 2kx2k detector size. The units are millimeters. There are room for approximately 90 orders (for each fiber) on the detector. The orders numbers start from below with number 69, and ends at the top with number 159. The length of the lines in the diagram is drawn to one FSR.

The FSR of order number 69 is 119 Å
The FSR of order number 159 is 22 Å

The red double line used to test the resolution belongs to order number 90 (about 10 mm from the bottom), and the four lines in the blue that was also used belong to order number 124 (at the center of the detector).