FIFI LS: the far-infrared integral field spectrometer for SOFIA

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ABSTRACT

FIFI LS is a far-infrared integral field spectrometer for the SOFIA airborne observatory. The instrument is designed to maximize the observing efficiency by simultaneous and nearly independent imaging of the field of view in two medium spectral resolution bands. Both spectral channels - covering a wavelength range of 42 to 110 microns and 110 to 210 microns respectively - allow diffraction limited spectral imaging. Reflective image slicers rearrange the 5x5 pixel field of view into the 1x25 pixel entrance slit of a grating spectrograph. Littrow mounted gratings with anamorphic collimators are used for spectral multiplexing with a spectral resolution between R = 1400 - 6500, depending on observing wavelength. Each spectral band employs two large format 25x16 pixel Ge:Ga detector arrays, axially stressed for the long wavelength band to achieve a longer wavelength response and slightly stressed for the short wavelength band. For each of the 25 spatial pixels, we are able to cover a velocity range of approximately 1500 km/s around a selected far-infrared line. This arrangement provides good spectral coverage with high responsivity. We present a summary of the FIFI LS design and the current status of instrument integration.

Keywords: Integral Field Imaging, Spectrometer, Far-Infrared, FIFI, FIFI LS, SOFIA

1. INTRODUCTION

Practically every type of spectrometer used for astronomical research suffers difficulties in imaging the three relevant astrophysical dimensions - the radial velocity and the two dimensions of the image field - onto a two dimensional detector array. Classical types of spectrometers force the observer to preferentially choose two of the three dimensions: for a long slit spectrometer a range of one spatial and one spectral coordinate at a given spatial coordinate and for a Fabry-Perot spectrometer a range of two spatial coordinates at a given wavelength.

In this paper we present the design of the the Far-Infrared Field-Imaging Line Spectrometer (FIFI LS[1–4]) instrument, which will allow so-called 3-dimensional imaging or integral field imaging in two nearly independent far-infrared wavelength bands: 42 to 110 μm and 110 to 210 μm. With FIFI LS, both spectral (radial velocity) and spatial (the field of view) information are obtained simultaneously without scanning a Fabry-Perot or multiple pointings of a long-slit spectrometer. This results in a dramatic increase in observing efficiency. Besides its obvious strength of obtaining a complete data cube in one single observation, the 3D imaging technique also produces highly reliable datasets due to the parallel and simultaneous data acquisition.

Astronomical observations in the far-infrared are not possible from the ground due to strong water vapor absorption, requiring stratospheric or space observatories. Far-infrared astronomy will take a major step forward with the unprecedented spatial resolution and sensitivity that the Stratospheric Observatory For Infrared Astronomy (SOFIA) can offer. The main scientific goals for FIFI LS include: (1) detailed morphological studies of the heating and cooling of nearby galaxies, (2) star formation and the interstellar matter under low metallicity conditions as found in dwarf galaxies, (3) active galactic nuclei and their environment, and (4) merging and interacting galaxies. Research of these astrophysical topics requires very high observing sensitivities and efficiencies. However, a comparably low spectral resolution (R $\sim$ 130 km/s) will be sufficient.

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2. INSTRUMENT DESIGN

2.1. Cryostat

In Fig.1 we present a longitudinal section of the FIFI LS instrument including optical components. The functional sub-groups of the instrument are:

- Vacuum vessel
- Boresight box and guider camera
- Mounting structure
- Liquid nitrogen vessel
- Liquid helium vessel
- Helium II vessel

The vacuum vessel is roughly 1 m × 1 m × 1 m and contains the three cryogen containers, the optics and the two detector arrays. The vacuum vessel consists of three individual shells, each milled out of one single block of aluminum. The main function of the vacuum vessel is to provide the vacuum needed to thermally insulation the cryogenic surfaces. Since all mechanical components are mounted on the vacuum vessel structure, it also forms the primary mechanical structure of the instrument.

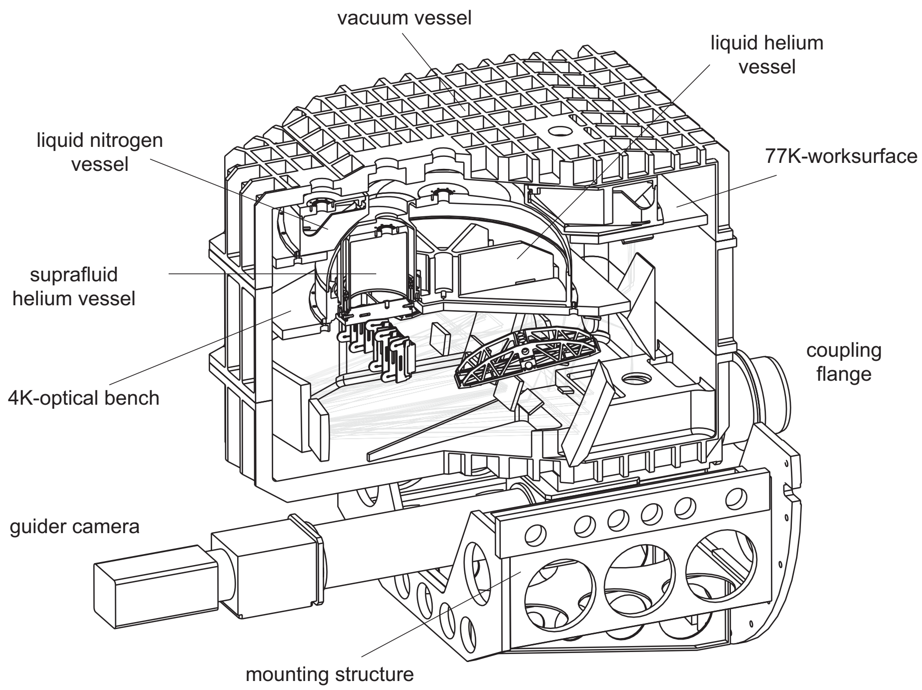

Figure 1. A cut through the FIFI LS cryostat. The optical components are mounted on the cryogenic plates. Light from the SOFIA telescope is entering the instrument from the right via the coupling flange.

The so-called boresight box is mounted onto the bottom of the vacuum vessel. It comprises an adjustable dichroic beam splitter separating the telescope light into two beams around the cut off wavelength of $\sim 2\ \mu$m.

The visible and near infrared light passes through the beam splitter and is used for telescope guiding. The mid- and far-infrared components of the incoming light are reflected into the cryostat by a thin polyethylene window. The polyethylene entrance window also acts as a pressure barrier between stratospheric pressure and the vacuum inside the instrument.

The cryogenic system of FIFI LS consists of three cryogen vessels that provide the temperature levels required in the instrument. A 31.5 liter liquid nitrogen container at 77K provides cooling for the liquid nitrogen work surface, the entrance optics (a rotating K-mirror and re-imaging optics) and the outer radiation shield. The 35 liter liquid helium vessel (4.2K) provides cooling for the liquid helium working surface, the entire spectrometer optics not including the detectors (for optical layout see Sect. 2.2) and the inner radiation shield. Since the detector arrays (see Sect. 3.3) require operating temperatures below 4K, they are mounted onto an additional 3.12 liter suprafluid helium vessel (a pumped reservoir for liquid helium at $\sim$ 1.9K).

All cryogen vessels are suspended by G-10 glass fiber and carbon fiber stand-offs respectively that provide high mechanical stability and low thermal conductivity. The maximum cryogen holding time is limited by the suprafluid helium reservoir: expected to be about 18 hours.

2.2. Optical Layout

FIFI LS is a two channel spectrometer that allows simultaneous observations in the wavelength bands 42 - 110 μm and 110 - 210 μm. The key to the 3D imaging capability is an image slicer system in each band, that rearranges the two dimensional 5$\times$5 pixel field along a 25 (+4)$\times$1 pseudo-slit (Fig.2) which can be easily fed into a grating spectrometer. Notice the deliberate 1 pixel gap between the 5 individual slices eliminating cross-talk between spatial pixels that are not adjacent in the original field of view like pixel I and II in Fig.2. In each channel, a large format 25$\times$16 pixel detector array is utilized.[5,6]

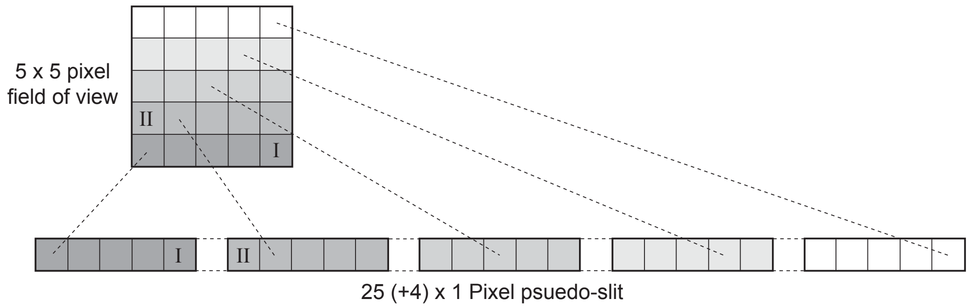

Figure 2. Illustration of the basic design premise for the FIFI LS image slicer. The optics slice the rows of the 5$\times$5 pixel field of view into a 25$\times$1 pixel pseudo-slit. The pixel gaps in the slit are added to reduce cross-talk between nonadjacent field pixels (e.g. pixels I and II).

Fig. 3 shows a schematic overview of the FIFI LS optical layout in the form of a block diagram. The first optical component is an adjustable dichroic beam splitter that reflects the incoming radiation into the FIFI LS cryostat and passes the visible and near-infrared radiation to a CCD guider camera. The reflected beam enters the vacuum vessel via a thin polypropylene window. The following entrance optics are cooled to 77 K in order to minimize background radiation. The entrance optics consist of a K-mirror assembly that compensates for sky rotation during integration and a Re-imaging mirror, which refocuses the beam onto the slicer mirrors. The Re-imaging mirror also creates a pupil where the beam enters the actual spectrometer part of the instrument forming a Lyot-Stop to minimize straylight. A far-infrared dichroic beam splitter close to the Lyot-Stop separates the long wavelength (110 - 210 μm) and short wavelength radiation (42 -110 μm) feeding the Blue and Red band of the instrument. Both spectrometer channels are designed very similar. The most important difference is that a set of re-imaging mirrors doubles the image size on the blue image slicer.

The actual slicer system is comprised of three sets of mirrors in groups of five individual mirrors. The first stack of mirrors (slicer mirrors) are slightly tilted with respect to the center slice, and spatially fan-out each row

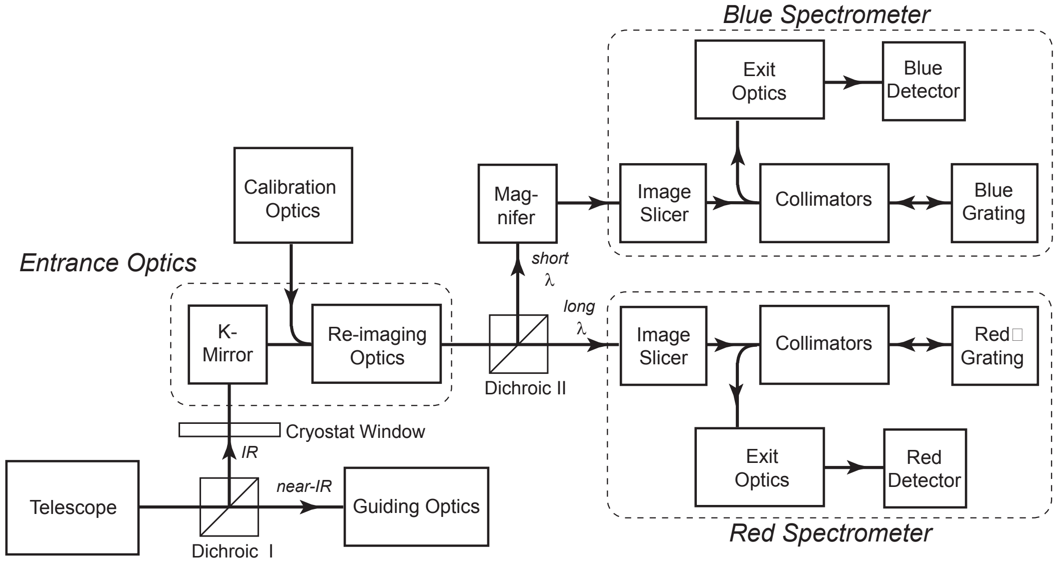

Figure 3. A block diagram of the FIFI LS optics. Calibration optics used to provide flat-fielding of the detector pixels can be switched into the path via a flip-mirror.

of the two dimensional field of view. The slicer mirrors have spherical surfaces and act as a field mirrors that image the pupil onto the second set of mirrors (capture mirrors). In the next step, the capture mirrors, designed as on-axis spherical biconics, refocus the beam onto the last set of mirrors (slit mirrors), thus forming the one dimensional pseudo-slit.

The slit mirrors again are spherical mirrors that are angled such that the 5 pupils are virtually re-imaged to a single pupil, which is then imaged onto the diffraction gratings by two anamorphic collimators. Since the gratings are mounted in Littrow configuration, the same collimators are used to refocus the dispersed beam at the output.

Each spectrometer channel needs a diffraction grating that is optimized for the respective waveband. Rigorous analysis of the grating efficiencies was carried out using PCGrate-1E Ver. 3.0, a program which fully solves the Maxwell equations with periodic boundary conditions. The grating parameters have been optimized to achieve highest efficiencies at the astrophysically most relevant wavelengths around 63 μm (emission line of [OI]) in the blue and around 158 μm (emission line of [CII]) in the red spectrometer band. Both gratings have grooves with triangular cross sections and groove depth of 145 μm and 46 μm for the red and blue grating respectively. The grooves are manufactured by diamond milling at Hyperfine, Boulder/Colorado (blue grating) and Zumtobel Staff GmbH, Dornbirn/Austria (red grating). The grating in the red spectrometer is operated in its first diffraction order only and reaches a theoretical efficiency of almost 98% at 148 μm. The blue grating is operated in first and second order to fully cover the wavelength band. The calculated efficiency is about 75% at the blaze wavelengths of 55 μm (1st order) and 90 μm (2nd order).

After spectral multiplexing in the spectrometers, anamorphic exit optics are used to scale the spectrum to accommodate the detector array dimensions in the spectral as well as in the spatial direction. The exit optics also form a pupil at a distance of 240 mm in front of the detector. Light cones attached in front of the individual pixel are designed to accept light from only a solid angle defined by this pupil. This arrangement forms a highly efficient straylight suppression system. Fig.4 shows a 3D-representation of the overall optical layout. The red channel is located in the upper, the blue channel in the lower part of the image.

In order to ensure diffraction limited performance as well as to prevent any deterioration of the instrument resolution or sensitivity due to diffraction effects, a detailed diffraction analysis has been performed using the software package GLAD Version 4.5. In addition, a full vectorial analysis has been carried out to check for

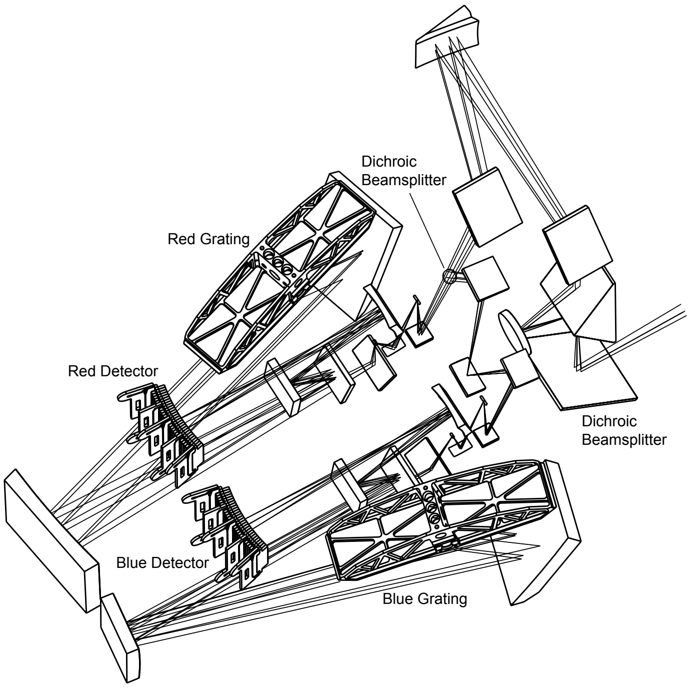

Figure 4. The optical system of FIFI LS. Light from the telescope enters at the right (close to 'Dichroic Beamsplitter').

polarization dependent diffraction effects.[7,8] Important results of the diffraction analysis are the estimation of the light loss on the individual optical components and the theoretical spectral resolution of the instrument. On the left panel of Fig.5 we show the integrated light loss from diffraction after each mirror surface. The throughput is normalized to 100% light at the slicer mirrors. As the analysis shows, most of the light is lost after the capture mirrors of the slicer assembly, which by design cuts into the diffraction pattern of the Slicer mirrors. Nonetheless, the light loss caused by diffraction and vignetting does not exceed 6% at most operating wavelengths. The right panel of Fig.5 shows the calculated spectral resolving power of FIFI LS as a function of observing wavelength.

3. STATUS OF INTEGRATION

3.1. Cryostat

The FIFI LS vacuum vessel consists of three individual shells. Since the alignment of the entire optical system of the instrument relies on the mechanical stiffness of the vessel structure, we have decided to mill each shell out of one solid piece of 6061 aluminum alloy. In this way, we also avoid welding seams, that are hard to FAA certify. All three shells have been machined and delivered by the manufacturer. Fig. 6 shows the assembled shells of the vacuum vessel mounted on the instrument integration cart.

The FIFI LS cryostat is directly attached to the science instrument flange (SI flange) of the SOFIA telescope using two bolts which in principle would be sufficient to carry all the loads that are required by FAA. To provide even higher stability required for the optical alignment, the instrument is additionally attached to a mounting structure (see Fig. 1), that is also attached to the SI flange by 13 bolts. As shown in Fig. 7, all parts of the cryostat mounting structure have been machined and are fully assembled.

The individual shells of the three cryogen containers (Sect. 1) have been successfully manufactured at various companies. Assembly of the containers requires welding, which was carried out at Probeam AG, Winterthur/Switzerland under certified conditions. This company was chosen because it is certified for electron

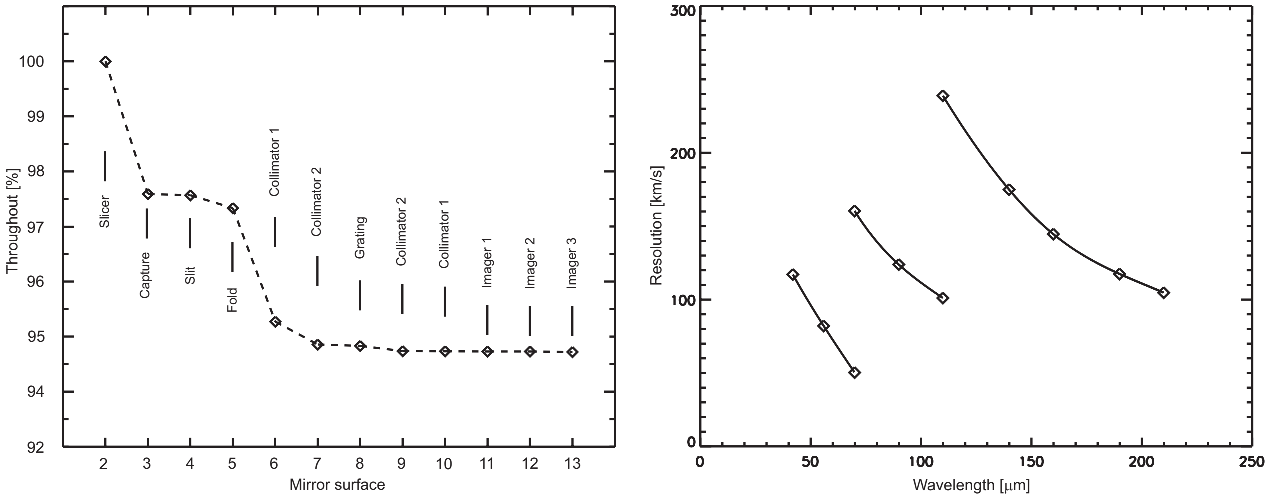

Figure 5. Left: The light loss through the optics due to diffraction and vignetting effects. Right: The simulated spectral resolution of FIFI LS.

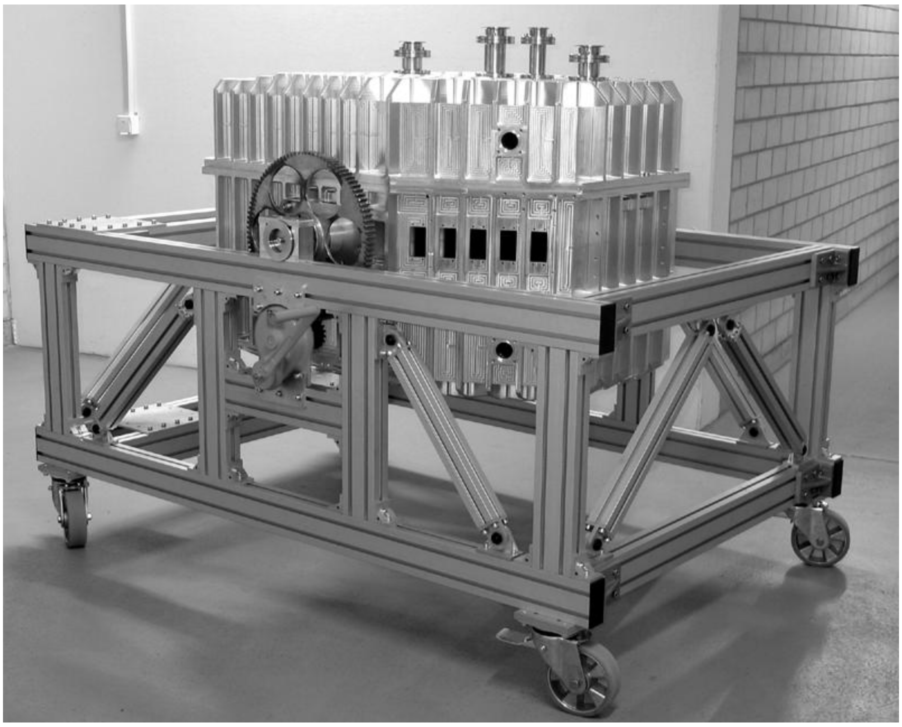

Figure 6. The FIFI LS vacuum vessel mounted on the instrument integration cart. The dimensions of the instrument are roughly 1 m × 1 m × 1 m.

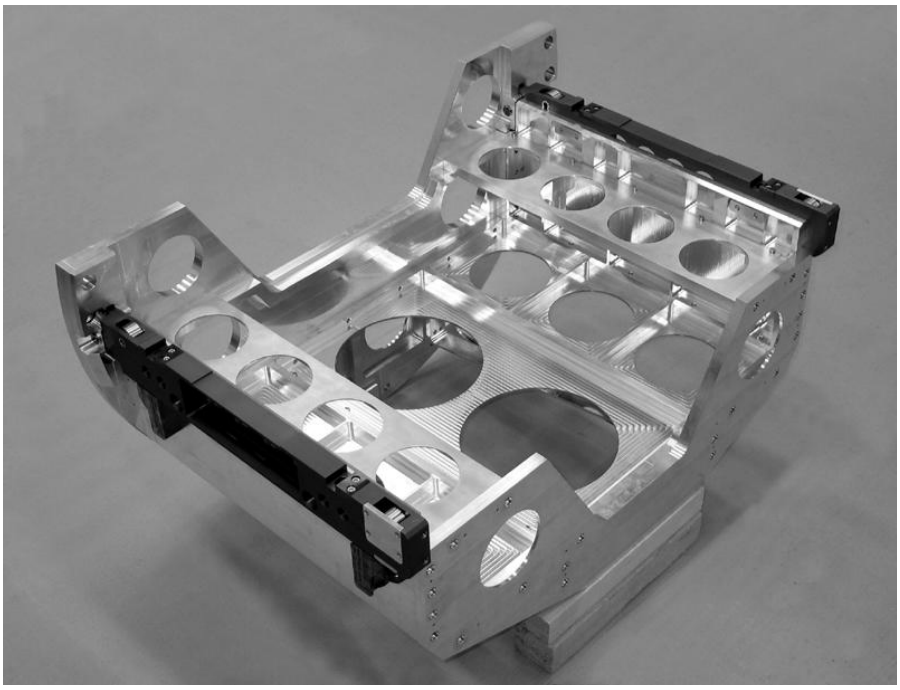

Figure 7. The fully assembled mounting structure of FIFI LS.

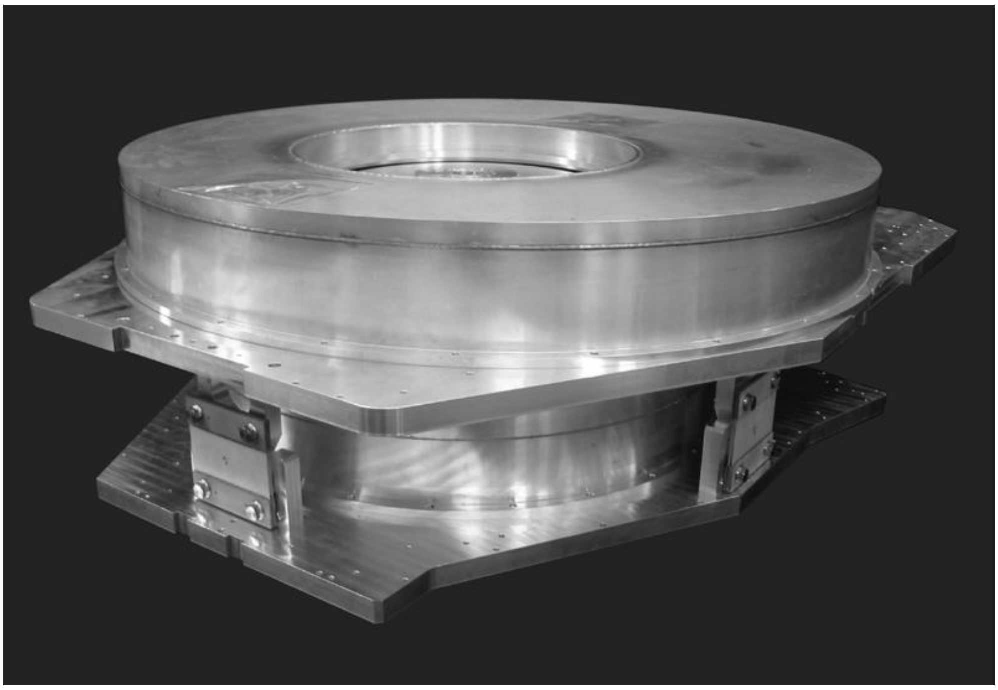

Figure 8. The preliminary assembly of the instruments cryogenic system. The assembly includes: the cryogen vessels, the cold worksurfaces (77K and 4K), and the G-10 and carbon fiber stand offs.

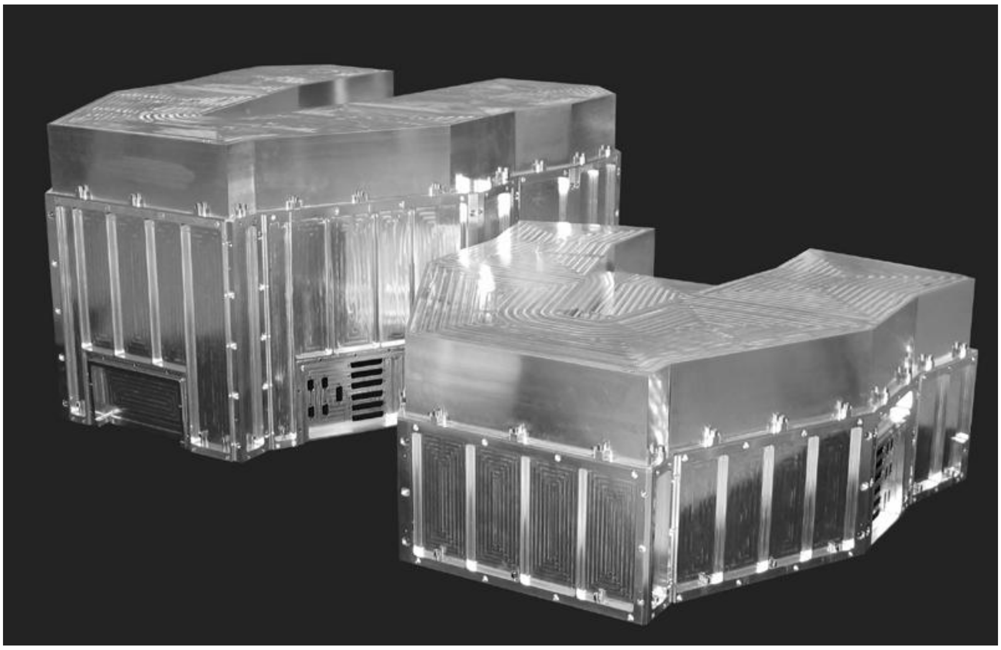

Figure 9. The radiation shields. The inner shield of the liquid helium system is in front and the outer shield of the liquid nitrogen system is in the background. Both shields will be covered with superinsulation on the outside and infrared black paint on the inside.

beam welding of aircrafts engine parts. A witnessed pressure test required by FAA authorities is planned in late July 2004.

In addition to the cryogen containers, the liquid nitrogen as well as the liquid helium worksurface are manufactured and prepared for installation of the optical components. Together with the assembled G-10 fiber glass and carbon fiber stand-offs and the welded and brazed bellows of the cryogen vessel necks, the entire cryogenic system of FIFI LS is ready for final instalation. In Fig. 8 we present picture of a preliminary assembly of the cryogenic system of FIFI LS including the cryogen vessels, both worksurfaces and the G-10/carbon-fiber stand-offs (compare to Fig. 1).

Finally, both radiation shields are manufactured and assembled. As shown in Fig. 9, the sides of the radiation shields are made from individual plates connected by bolts and pins. Only the top parts are milled from one single piece of aluminum. This design was chosen to assure optimum thermal contact together with high mechanical stability at a low structural mass.

3.2. Optical Components

All optical components - with the exception of the dichroic beam splitters - used in FIFI LS are aluminum mirrors manufactured by diamond turning or milling respectively. The surface tolerances we require for the machining process are a geometrical error of less than 2 μm ($\sim \lambda/20$ for the shortest wavelength), and a surface roughness of better than 100 nm. The demand for the small surface roughness seems exaggerated for far-infrared optics, but a good surface quality greatly facilitates the alignment of the optical components, since visible adjustment lasers can be used.

To date, almost all mirrors including spares are already in-house. The only mirror that has not been delivered yet is a collimator mirror for the red spectrometer; the largest mirror in the instrument. The missing collimator mirror is currently in manufacture at the Labor für Mikrozerspanung (LFM) in Bremen/Germany. The reflectivity of aluminum in the far-infrared is high enough to leave the mirrors uncoated, but since surface oxidization

Figure 10. The FIFI LS optical system. Dichroic beam splitters, diffraction gratings and detector arrays are not installed. Compared to Fig. 4 the picture is upside down.

would degrade the optical properties over time, all optical surfaces are covered with a protective coating of 5 μm gold on top of 2 - 5 nm chromium.

In addition to the actual optical components, all mirror holders and consoles have been machined as well, so that the assembly of the optical system and the preliminary alignment of the components could be initiated. In Fig. 10 and Fig. 11 we present the assembly of the FIFI LS optics. The assembly does not including dichroic beam splitters, diffraction gratings, and detector arrays.

As mentioned before, both gratings are machined by diamond milling. Since many thousand grooves have to be cut, one at a time, with very high precision, the machining of the gratings is much harder and also much more time consuming then the manufacture of a mirror surface. The grating for the short wavelength spectrometer was manufactured in acceptable quality by Hyperfine, Boulder/Colorado, and has already been delivered. The red grating currently in manufacture at Zumtobel Staff, Dornbirn/Austria. This company already performed detailed investigations of the manufacturing process and has successfully machined a smaller test piece.

The operating wavelength of the spectrometers is adjusted by tilting the gratings. To reach the spectral resolution of $\sim$100 - 250 km/s, the gratings have to be moved and controlled with a precision of less than three arcseconds at 4K. The gratings are actuated by a two stage tilting mechanism. The first coarse positioning stage, consists of a support structure mounted onto the grating. The support structure is driven by a roller screw via a sine bar mechanism. A thermally isolated stepper motor at liquid nitrogen drives the roller screw. For the second fine positioning stage we use a stack of two PZTs in series, that drive the grating directly with respect to the support structure via a lever arm.

The cold grating drive mechanism is fully assembled and tested at 4K. The position read out by Inductosyn rotary transducer is operational and has been verified. Unfortunately both PZTs used in the grating drive where destroyed during cool down due to electrical discharges. The manufacturer has provided new and improved PZT

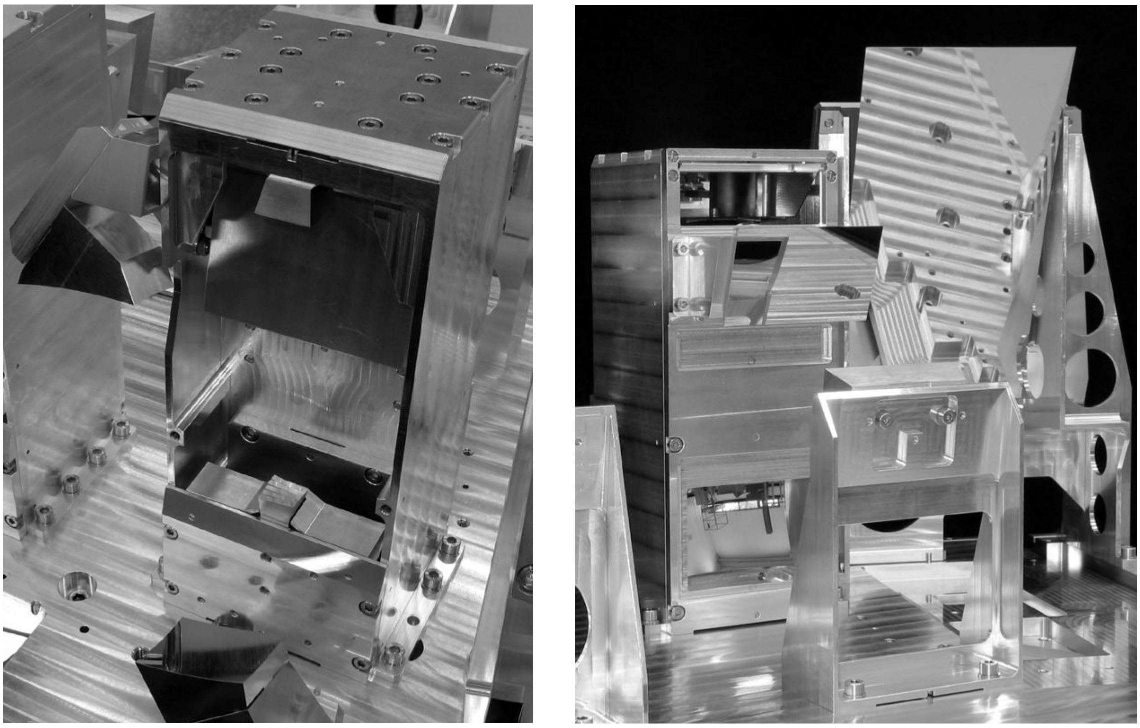

Figure 11. Details of the FIFI LS optics. The left panel shows the image slicer console and two of the magnification mirrors of the blue spectrometer. In the right panel a collimator mirror together with the imaging mirrors at the exit of the spectrometer and the image slicer console of the red is shown.

stacks that are based on thick film instead of sputtered electrodes. The new PZTs have passed cold tests and thermal cycling. The next iteration of grating drive cold test using these PZTs is currently in preparation.

3.3. Detectors

FIFI LS will use large scale 400 pixel detector arrays to cover the wavelength range of 42 - 110 μm and 110 - 210 μm of the two parallel spectrometers. For both arrays we use Gallium doped Germanium (Ge:Ga) photoconductors, which have a high sensitivity up to 120 μm. Application of mechanical stress of $\sim$600 N/mm^2 shifts the wavelength response of the detector material to almost 220 μm. Accordingly we use two 16×25 pixel Ge:Ga detector arrays, one stressed in the long wavelength spectrometer and another only slightly stressed for the short wavelength spectrometer.

The entire stressed array including two spare modules are fully assembled and has passed cool down tests. In Fig.12 we show the entire array of stressed FIFI LS flight detectors. For the unstressed array all component parts have arrived in-house, but only seven modules have been assembled to date. The noise equivalent power (NEP) has not been tested on the flight models yet, but from investigations of stressed prototype modules[5] we derive a NEP of about 1.5×10^{-16} W Hz$^{-1/2}$. The quantum efficiency assuming background limited performance of the entire system ranges from 25% to 35%.

An active Cold Read-out Electronic circuit (CRE)[9] is located at the back end of each detector module. The CRE is a specially designed CMOS circuit developed for the Herschel-PACS[10] instrument by IMEC, Leuven/Belgium and can be operated at a temperature of below 4K. The CRE circuits are designed to amplify and multiplex the signal of the 16 pixels in one detector module. The first prototypes of CRE circuits are already delivered, but failed to meet the noise specifications due to transient effects after reset of the integration capacitors.

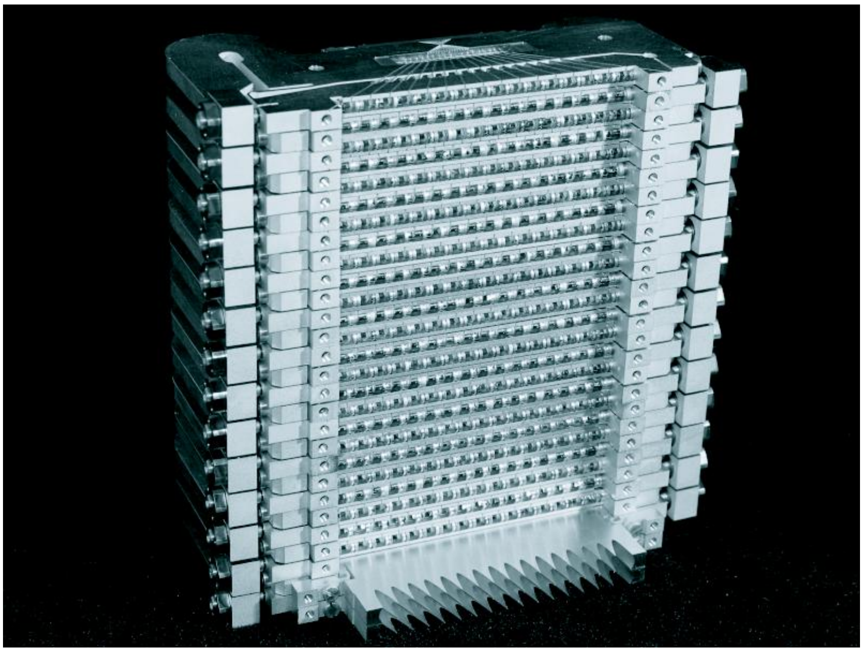

Figure 12. The 25 (+2 spares) stressed Ge:Ga detector modules of FIFI LS. the lower two modules are equipped with light cones.

4. CONCLUSION

Integral field instrumentation has proven to be a very useful tool to probe many astronomical problems. However until recently, far-infrared integral field instruments were not technically feasible due to the limited size of the detector arrays. With the construction of large format detectors, we have been able to design the first integral field instrument in the far-infrared using a novel design with reflective slicer mirrors. In this paper we presented the overall design concept of FIFI LS together with a status report on the integration of the instrument. To date many important parts of FIFI LS have been designed, manufactured and assembled, including the vacuum vessel, mounting structure, cryogenic system, and optical components. Tests of these sub-systems are currently prepared. Preliminary results have already verified the design concepts.

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