R. Klein, A. Poglitsch, W. Raab, N. Geis, M. Hamidouche, L. W. Looney, R. Hnle, M. Schweitzer, W. Viehhauser, R. Genzel, E. E. Haller and Th. Henning, "FIFI LS: the far-infrared integral field spectrometer for SOFIA", Proc. SPIE 6269, 62691F (2006).

http://dx.doi.org/10.1117/12.671505

FIFI LS: The Far-infrared Integral Field Spectrometer for SOFIA

R. Klein[a], A. Poglitsch[b], W. Raab[b], N. Geis[b], M. Hamidouche[c], L. W. Looney[c], R. Hönle[b], M. Schweitzer[b], W. Viehhauser[b], R. Genzel[b], E.E. Haller[a] and Th. Henning[d]

[a]University of California, Berkeley, USA;
[b]Max-Planck-Institut für extraterrestrische Physik, Garching, Germany;
[c]University of Illinois, Urbana-Champaign, USA;
[d]Max-Planck-Institut für Astronomie, Heidelberg, Germany

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. We present a summary of the *FIFI LS* design and the current status of instrument development. Its unique features as the large far-infrared photoconductor detectors, its integral field concept, and control system will be highlighted. Special attention will be given to the Extended Observing Opportunity Program, which will allow general access to *FIFI LS* on SOFIA.

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

1. INTRODUCTION

NASA together with the German DLR is developing the unique airborne observatory SOFIA (Stratospheric Observatory For Infrared Astronomy) – a B747-SP with a 2.5 m telescope built in.[1] SOFIA will make the full infrared wavelength range routinely accessible for more than a decade at unprecedented resolution by carrying its telescope upto 45,000 feet leaving the blocking water vapor behind. SOFIA will also be a unique platform to test the newest instrumentation. It is planned that SOFIA is routinely equipped with the new instruments and detectors as technology advances.

We are developing the *FIFI LS* (Far-Infrared Field-Imaging Line Spectrometer), one of the first-light instruments for SOFIA, employing two of the largest far-infrared photoconductor arrays to date.[2–6] *FIFI LS* will offer simultaneous spectroscopy of two spectral lines, one in each of its two nearly independent spectrometers with a wavelength coverage of 42 to 110 μm and 110 to 210 μm, respectively, at moderate spectral resolution, 50 – 250 km/s. Our instrument will allow efficient mapping of these lines employing so-called 3-dimensional imaging or integral field spectroscopy. Using a grating spectrometer and an image slicer (Sect. 2.2), a spectrum with considerable wavelength coverage is obtained for every pixel in a square field of view. This results in a dramatic increase in observing efficiency especially when mapping lines over an extended area compared to a scanning Fabry-Perot or a long-slit spectrometer. Furthermore, the simultaneous acquisition of the spatial and spectral information ensures homogeneity of the observed data and yields redundancy in the data useful for reliable data reduction and removal of instrumental effects. In this paper, we present the design and status of development of *FIFI LS*. In a second paper, the recent characterization of the system performance and sensitivities of *FIFI LS* are discussed.[7]

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 metalicity conditions as found in dwarf galaxies, (3) active galactic nuclei and their environment, (4) merging and interacting galaxies, and (5) photon dominated regions in galactic high-mass star-forming regions. Efficient mapping and sensitivity is important in all of the above research areas. The spectral resolution is fully adequate for the mainly extra-galactic research planned for *FIFI LS* and allows an instantaneous coverage of the rotation curve of a galaxy.

Further author information: (Send correspondence to R.K.)
E-mail: `r_klein@calmail.berkeley.edu`, `http://fifils.mpe.mpg.de`

Ground-based and Airborne Instrumentation for Astronomy, edited by Ian S. McLean, Masanori Iye,
Proc. of SPIE Vol. 6269, 62691F, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.671505

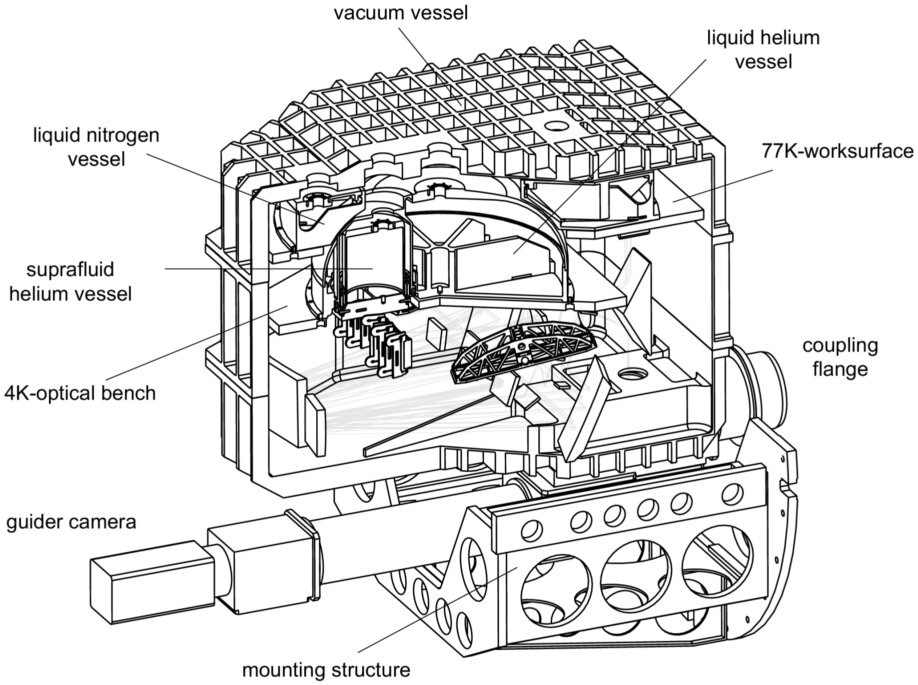

Figure 1. A cut through the *FIFI LS* cryostat. The optical components are mounted on the work surfaces attached to the cryogen vessels. Light from the SOFIA telescope is entering the instrument from the right via the coupling flange.

2. INSTRUMENT DESIGN

In this section, we want to give a short overview over the design of *FIFI LS* and how it works. The instrument is directly attached to the nasmyth tube of the SOFIA telescope. The light from the telescope comes through the nasmyth tube and enters the *FIFI LS* cryostat through the so-called boresight box. A dichroic mirror in the boresight box reflects the far-infrared beam into the cryostat while transmitting the visible light to a CCD camera used for guiding. Figure 1 shows 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
- Superfluid helium vessel

The spectrometers and other optical components are mounted to the 4 K- and 77 K-work surfaces (optical benches). The detector is mounted to the work surface of the vessel for the superfluid helium. In the following subsection, the cryostat, the optics, and the detectors are described.

2.1. Cryostat

The main part of *FIFI LS* is the vacuum vessel roughly 1 m × 1 m × 1 m in size. It 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 insulate the cryogenic surfaces. Since all mechanical components are mounted on the vacuum vessel structure, it also forms the primary mechanical structure of the instrument. A CCD-camera under the cryostat is used for guiding and focusing the instrument. To feed the CCD-camera with visible light, a so-called boresight box is mounted onto the bottom of the vacuum vessel. Its main component is 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 reaches the CCD camera. The mid- and far-infrared components of the incoming light are reflected into the cryostat. Prior to mounting *FIFI LS* to the telescope, the dichroic is adjusted in the lab, so that the far-infrared focus of *FIFI LS* and the optical focus of the CCD-camera coincide.

The cryogenic system of *FIFI LS* consists of three cryogen vessels that provide the temperature levels required in the instrument. A 31.5 l liquid nitrogen container at 77 K 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 l liquid helium vessel (4.2 K) 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. 2.3) require operating temperatures below 4 K, they are mounted onto an additional 3.12 l superfluid helium vessel (a pumped reservoir for superliquid helium at ~ 1.9 K). 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.

2.2. Integral Field Spectroscopy

FIFI LS is a two channel spectrometer that allows simultaneous observations in the wavelength bands 42 – 110 μm and 110 – 210 μm. An interchangeable dichroic mirror splits the far-infrared beam reflecting the shorter wavelength to the "blue" spectrometer and transmitting the longer wavelengths to the "red" one. An image slicer system in each band re-arranges the two dimensional 5×5 pixel field-of-view 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. The grating spectrometer disperses then the incoming light. A large format 25×16 pixel detector array in each spectrometer receives then the spectrum from each of the 25 pixels on a column of 16 pixels.[8,9] More details on the optical design of *FIFI LS* can be found elsewhere.[10,11]

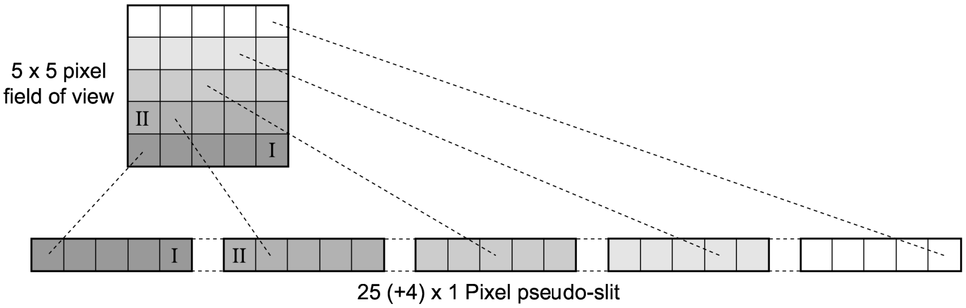

Figure 2. Illustration of the basic design premise for the *FIFI LS* image slicer. The optics slice the rows of the 5×5 pixel field of view into a 25×1 pixel pseudo-slit. The pixel gaps in the slit are added to reduce cross-talk between nonadjacent field pixels (e.g. pixels I and II).

2.3. Detector Arrays

FIFI LS uses two detector arrays, one for each of the two spectrometers. Germanium Gallium-doped photoconductors are used which are sensitive between 40 and 120 μm, and, with the application of about 600 N mm^{-2} of stress, their wavelength sensitivity shifts to 100 - 220 μm.[12,13] Thus, an unstressed and a stressed detector array are used in *FIFI LS* for the short and long wavelength spectrometer, respectively.[8] Both arrays have 16×25 pixels putting them among the largest of their kind. The detector array consists of 25 modules each corresponding to one of the 5×5 pixel field-of-view. Each module holds a stack of 16 pixels which allows to apply the same stress to each of the 16 pixels ensuring a uniform response of the pixels.

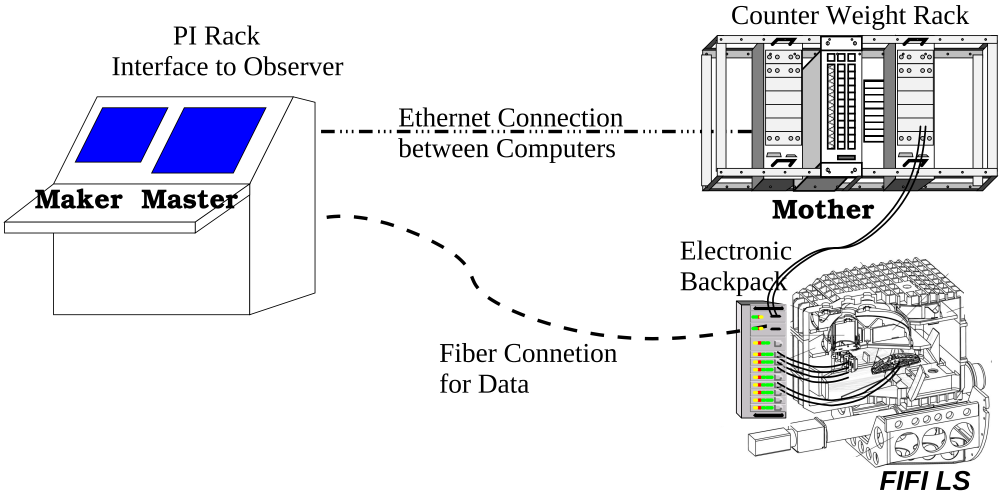

Figure 3. The three main entities in the *FIFI LS* control system: the user accessible PI rack with two PCs (Maker and Master), the counter weight rack on the telescope with the control PC (Mother) and various drivers, and *FIFI LS* with an electronics backpack. See Sect. 2.4 for the details.

The detectors are read out with an active Cold Read-out Electronic circuit (CRE)[14] located immediately behind each detector module. The CRE is a specially designed CMOS circuit developed for the Herschel-PACS[15] instrument by IMEC, Leuven/Belgium and can be operated at temperatures of below 4 K. The CRE circuits are designed to amplify and multiplex the signal of the 16 pixels in one detector module. The analog detector signals are send over triax cables with active shield to warm pre-amplifiers mounted on the inside of the cryostat wall. After amplification the analog signals get digitized and the signals of the 25 modules get multiplexed again immediately outside of the cryostat. The digital data stream of each detector is then sent to the data-taking computer over an optical link.

2.4. Control System

The CREs are driven by a clock signal and a synchronization line provided by the "pattern generator". "The pattern generator" is a kind of a sequencer or programmable logic controller realized with a parallel I/O-card including a buffer memory (NI PCI-6534). The data words in the card buffer get clocked onto the parallel output lines by an external or internal clock signal. Two bits of the data words correspond to the clock and synchronization line for the CREs. The other bits get onto the other lines controlling all the other subsystems of *FIFI LS* which need to be synchronous with the detector read-outs. The buffer memory of the card can be written asynchronously by the PC which controls the *FIFI LS* subsystems, called Mother*. This allows the non-realtime operating system of mother to control the instrument virtually in real-time.[16] A second card of the same type in the PC Maker allows its non-realtime operating system to record the detector data which arrives in "realtime".

Due the layout of SOFIA, the computers and electronics are located in three different locations in the aircraft (Fig. 3). The only observer accessible location during flight is the principle investigator (PI) 19″-rack. Obviously, that is the place for the PC called Master, which runs the graphical user interface (GUI) to command the instrument and telescope. The communication between Master and to the other computers of *FIFI LS* and the telescope are distributed by files on a shared file system shared over Ethernet (via optical link). This messaging system is also used by the SOFIA instruments GREAT and CASIMIR. It has actually been developed at for the KOSMA telescope[17] and is in use at other observatories, too. The messages of Master reach the PC Mother in the counter weight 19″-rack (CWR) via the shared file system. The CWR is mounted on the telescope and is used to balance the telescope *and* it is close to *FIFI LS*. The CWR also contains all the other electronics to drive mechanical parts of *FIFI LS* and to receive the signals from various position and temperature sensors in *FIFI LS*. In order to avoid ground loops all the signals are opto-coupled between the CWR and the electronic backpack mounted to the instrument. Apart from forwarding the opto-coupled signals into the cryostat, the backpack contains the warm read-out electronics that is driving the CREs and digitizing and multiplexing the analog signals coming from the

---

[*] Named after the ship computer in the film Alien

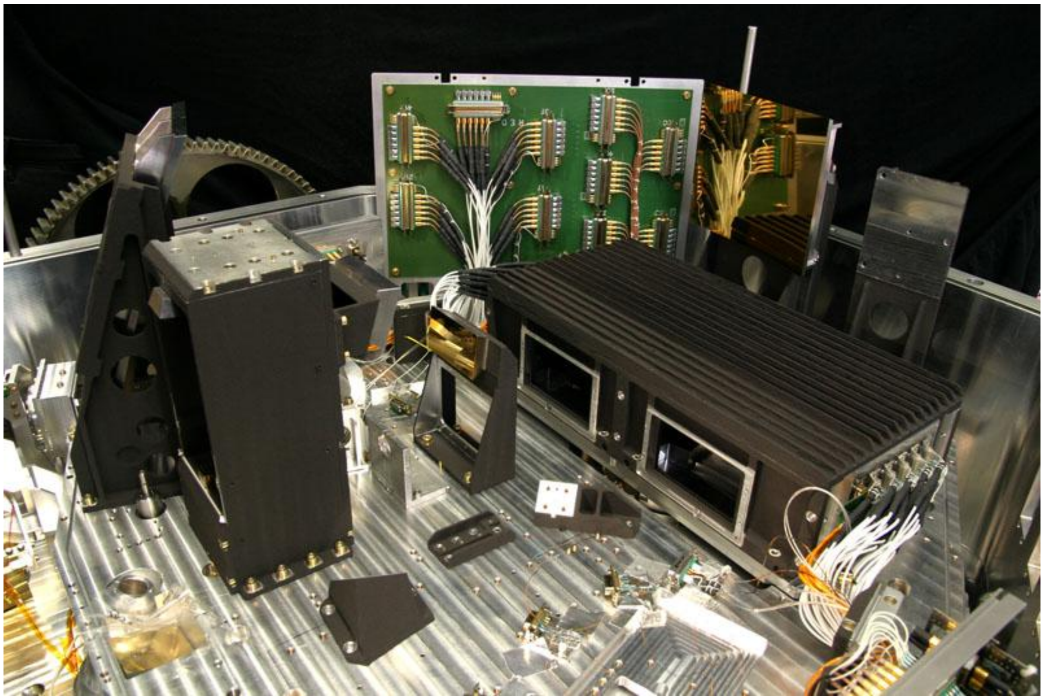

Figure 4. Integration in progress: The 4 K-work surface from left to right: collimator, the image slicer tower, exit optics, detector housing (on 1.9 K-work surface), collimator; in the back: pre-amplifier board with data cables.

CREs. The data stream it creates get then sent directly over a fiber connection to the distant PI rack, where the PC Maker receives the data for archiving, on-line reduction, and display. The fiber connections to and from the PI rack are supplied by SOFIA to allow connections between the PI Rack to the distant and moving CWR and science instruments.

3. STATUS OF INTEGRATION

The cryostat and the long wavelength ("red") spectrometer are fully integrated and tests of the instrument to characterize its performance are on-going.[7] The cryostat has undergone many successful cool-down cycles. All optical components of the "red" spectrometer and the common fore-optics (K-mirror) are aligned on the work surfaces of the cryostat. Figure 4 shows the open *FIFI LS* cryostat during the integration. Not all detector modules of the "red" detector array have been integrated (Fig. 9). In the following the details of the integration done and status of the instrument are discussed.

3.1. Cryostat

After the successful certification of the vessels for the cryogens by the FAA[†] as pressure vessels[‡], the cryostat could be integrated. The vacuum vessel consists of three individual shells (Fig. 1). All parts inside the vacuum vessel are mounted to the middle shell, so that the upper and lower shell can be removed to access the inside. Though, the vents and filling necks of the cryogen vessels reach through the upper shell. The cryogen vessels are fitted into each other like matrioshka-dolls to shield the inner colder vessels from the warm outer parts (Fig. 1). Likewise, the work surfaces are covered with radiation shields, one for each temperature level. The radiation shields and cryogen vessels are covered with super-insulation where space allows it and otherwise with aluminum foil to minimize the absorption of thermal radiation. Tests and measurements proved that the cryostat is performing well. Hold times of the cryogens are longer than 24 hrs, which allows convenient filling cycles. Temperatures below 2 K for the detectors can well be reached by pumping on the small liquid helium vessel and reaching the superfluid phase. The 4 K-work surface cooled with normal liquid helium cools to 4.8 K. The optics and

---

[†] Federal Aviation Administration

[‡] Except when pumping on the vessel for superfluid helium, the three vessels are at normal pressure, but inside a vacuum vessel. A yet higher overpressure can occur at accidental vacuum loss and subsequent rapid boil-off of the cryogens.

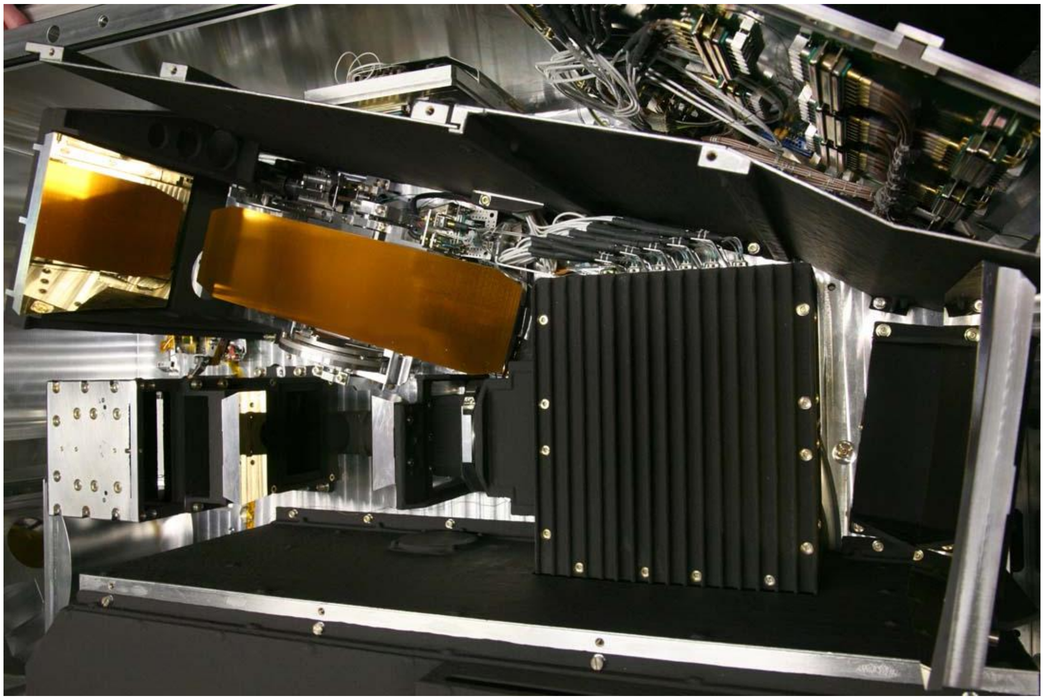

Figure 5. The "red" spectrometer: The two collimators are on the extreme right and top left. The grating on its drive assembly is next to the left collimator. Below the grating, there are the exit optics and the slices tower to the left. The black box on the right is the detector housing.

most baffles mounted to it reach about the same temperature. The large shield remains at a temperature of 5.6 to 5.8 K. The resulting background emission is at an acceptable level.

3.2. Optical Components

The "red" spectrometer and the K-mirror have been integrated on the respective work surfaces in the cryostat. Figure 5 allows to see the grating, part of the optics, and the closed detector housing between the baffles on the 4 K-work surface in the cryostat. Baffles and mirror consoles have been coated black to reduce stray-light and unwanted reflections (ghost images). The black paint used is NEXTEL®-Suede Coating by Mankiewicz Gebr. & Co. (Hamburg, Germany). Glass beads with sizes from 20 μm to 200 μm in diameter were added to increase the absorption in the mid- and far-infrared. The coating is a multi layer coating including three layers of paint with glass beads of different sizes. The lowest layer contains the largest beads and the top layer the smallest.

The "red" grating has been manufactured with great precision by Zumbtobel Staff, Dornbirn/Austria. The challenge in cutting this grating was not the grating constant of 120 μm but the 145 μm deep groves without leaving burrs. Figure 6 shows the gold coated grating and the clean profile of the grating. The grating is gold coated to protect the aluminum surface from corrosion.

The optical components have been aligned and tested to be stable during cool-down cycles. The 3 mirrors of the K-mirror had to be aligned so that the optical axis and the mechanical rotation axis coincide (Fig. 7). Another demanding alignment tasks has been the alignment of the image slicer: the 3 sets of 5 mirrors, which re-arrange the square field-of-view onto the entrance slit of the spectrometer and recombine the resulting 5 pupils onto the grating. Figure 8 shows the capture mirrors of the image slicer during alignment. The spots in the center of the mirrors are images of a light source in the center of the Lyot-stop showing that the five pupils which the slicer mirrors created are centered on the capture mirrors.

A black-body source as been installed in the 77 K-volume. The black-body source is a small aluminum plate that has been painted black. A temperature sensor is attached to allow flux calibration of the detectors. You find more on the calibration in our other *FIFI LS* paper in this volume.[7] Later on the black-body will be replaced by a calibration source

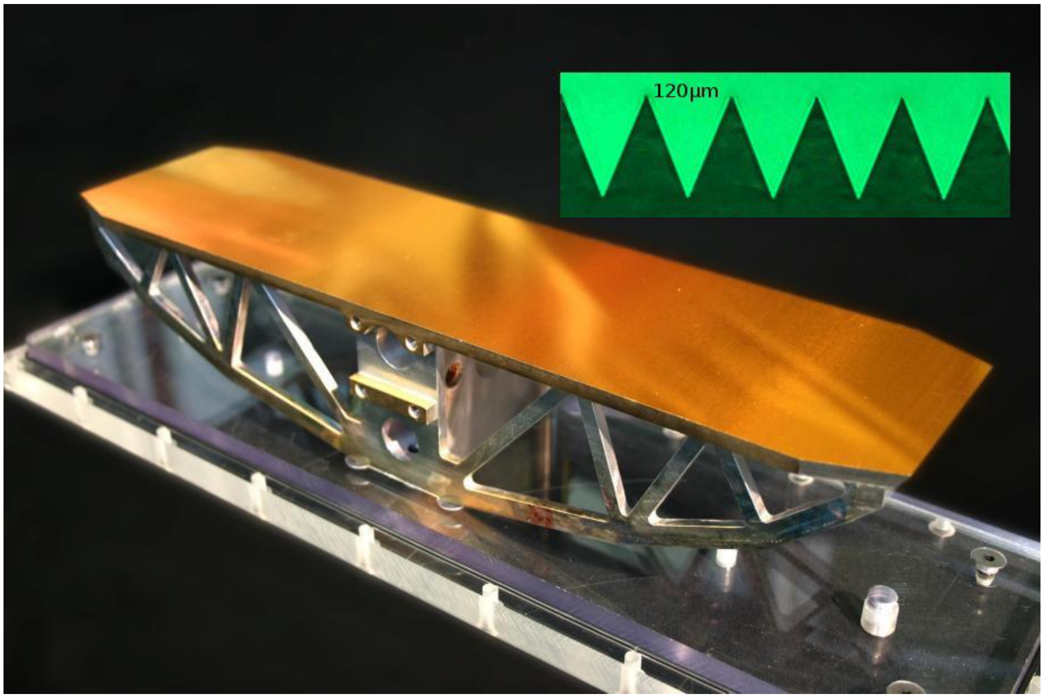

Figure 6. Gold coated "red" grating and inset with microscopic image of the grating profile (grating constant 120 μm).

providing a uniform illumination of the detector to monitor the detector responsivity during observations and to allow flat-fielding, i.e. calibrating-out sensitivity differences of the detector. The uniform illumination is achieved by placing an integrating sphere in front of a black body at roughly the telescope's temperature (240 K). The integrating sphere also dilutes the black-body radiation to simulate an emissivity of 15% like the SOFIA telescope system.

3.3. Cryo-mechanics

Several cryo-mechanism are needed to change to optical configuration. They are integrated and undergo testing. First of all, there is the grating drive to tilt the grating which selects the observing wavelength. To reach the spectral resolution of $\sim$100 - 25 km/s, the grating has to be moved and controlled with a precision of less than three arc-seconds at 4K in a flying aircraft. 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 stepper motor on the 77 K-work surface drives the roller screw. Thermal isolation is achieved by a magnetic clutch which acts through the radiation shield. For the second fine positioning stage we use a stack of two PZTs in series, that drive the

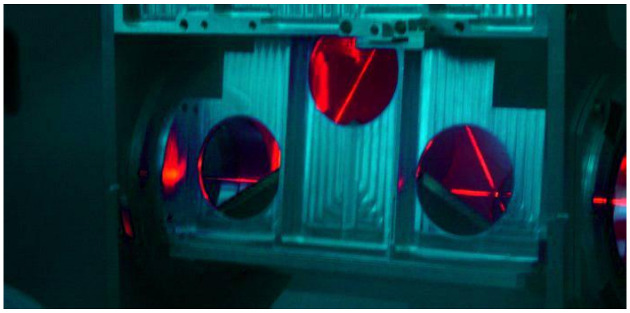

Figure 7. Alignment of the K-mirror using a laser to check the coincidence of the optical and mechanical rotation axis.

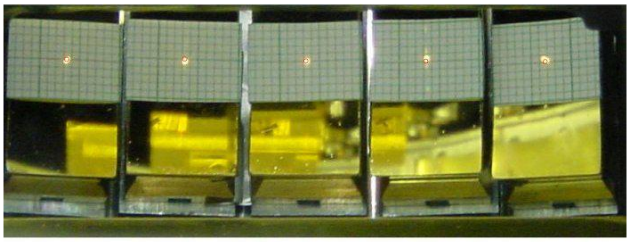

Figure 8. Capture mirrors of the image slicer optics during alignment verification with paper screens on them. One can see the image of the pupil center on mirrors.

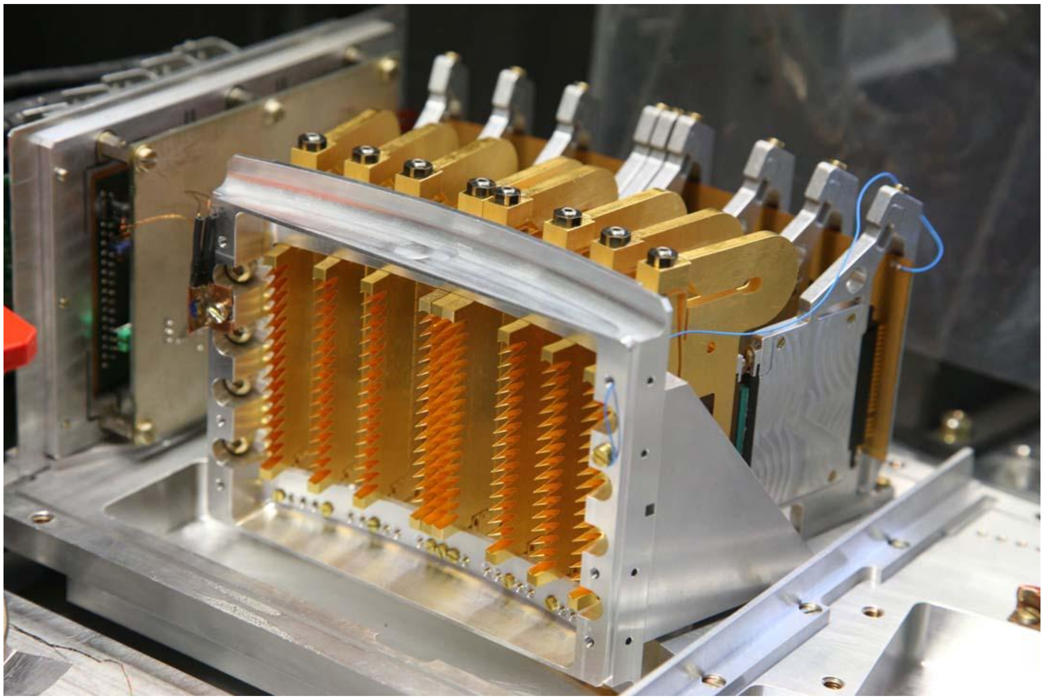

Figure 9. Nine detector modules in the "red" detector housing. Gold coated light cones, or light guides, are in front of the detector modules. The screw applying the stress to the column of detector pixels in the detector modules can be noticed on top of the modules. In the back, the CRE housings can be seen with spring contacts to a flexible circuit board for the electrical connection.

grating directly with respect to the support structure via a lever arm. The position is read-out by an Inductosyn® rotary transducer. The high voltage supply driving the PZTs and the coarse-drive stepper motor are controlled by a PC104-system in the CWR running a PID-loop using the Inductosyn® readings conditioned by custom electronics as input.

To feed the two spectrometers, a dichroic mirror in the 4 K-volume is used. The dichroic needs to be interchangeable to optimize observations around $110\,\mu$m, the upper/lower end of the wavelength range of the "blue"/"red" spectrometer. A stepper motor mounted in the 77 K-volume and thermally isolated from the 4 K-work surface moves a cart with the two dichroic mirrors via a drive rod. The "blue" spectrometer is not yet integrated, but the filter changer to interchange the order-sorting filter in the "blue" spectrometer, has been built and integrated. It is driven by a synchronous motor specificly designed for *FIFI LS* working at 4 K. Two more mechanism have been integrated fully on the 77 K-work surface: the K-mirror to de-rotate the sky image coming from the horizontally mounted telescope, and the flip-mirror, which switches the optical path between the calibration source and the regular path to the telescope.

3.4. Detectors

The "red" detector is not fully integrated into *FIFI LS* though all detector modules are available. There are different versions of the latest CRE module development available to us. Thus, only a few CRE modules have been integrated in order to test which CRE type performs best. In first tests, nine detector modules and CREs have been integrated into the detector housing as Fig. 9 shows. The modules were placed, so that they cover the central cross and the four corners of the field-of-view. The 16 pixels of each of modules receive the spectrum from each of these pixels in the field-of-view. Two of these modules are actually "blue" detector modules, i.e. unstressed detector pixels, whereas the remaining seven modules are "red" (stressed) modules. That way, we can characterize the "red" and "blue" detector modules in the same tests. For further tests, one "blue" and five "red" modules were added, so that we are running test with 15 modules altogether.[7]

3.5. Control System

The control system is still in its laboratory configuration which is somewhat simplified over the flight configuration laid out in Sect. 2.4. The custom warm and cold read-out electronics is working in the flight configuration. Most of the electronics backpack is already in flight configuration. The exceptions are simpler connection to the PCs Mother, and Maker. The data is sent from the backpack to Maker over short normal cables rather than over $\sim$30 m of fiber cable as required in the aircraft. The data connection over fiber has been tested separately. In the lab, the functionalities of Master and Mother can be combined in one PC, because the restrictions not to access Mother in the CWR only apply in the aircraft and not in the lab. The communication between Mother and Maker over the shared file system has been tested separately.

4. EXTENDED OBSERVING OPPORTUNITY PROGRAM

The science instrument being developed for SOFIA can be divided into two categories: Facility Science Instruments (FSI) and Principle Investigator Science Instruments (PSI). The FSI are handed over to SOFIA after their completion and get maintained and operated by the observatory. The PSI remain with the Principle Investigator for maintenance, operation and *upgrade*. The FSI are open to every observer and are built and documented for general use, whereas the PSI are instruments with a more experimental setup not for general use. *FIFI LS* is built as PSI and we are willing to support general observers to use *FIFI LS* as PSI, but our resources are limited and possibly not all request can be supported. But since *FIFI LS* covers an important range in spectral resolution and wavelength coverage of SOFIA, the observatory and we have agreed to install the so-called Extended Observing Opportunity Program (EOOP). Under this program, we will streamline the use of *FIFI LS* for common observing techniques. These observing modes will then be available to the general observers just as if *FIFI LS* was an FSI. Data reduction software (pipelines) and documentation will be supplied, too, as for the other SOFIA FSI. The instrument itself will remain with us for further upgrades and maintenance as a PSI, but this will remain transparent for the observer. To the general observer, it will be as if SOFIA has gained a facility far-infrared spectrometer.

5. SUMMARY

FIFI LS is one of the first-light instruments for NASA's airborne observatory SOFIA. It is designed and built to make efficient use of this unique platform by providing an far-infrared imaging spectrometer. We presented the design of our instrument and showed that the integration of *FIFI LS* is complete for end-to-end test which are currently conducted. The cryostat hold times are within the specifications. The optical components, baffles, and shields reach sufficient temperatures. The "red" spectrometer is fully integrated including calibration sources. The respective detector is integrated in part to accommodate also "blue" detector modules for detector and electronics testing. The read-out electronics does not introduce excessive noise. Control software and electronics are in place. The test results show that *FIFI LS* is working and can observe background limited on SOFIA.[7] Under the EOOP, our instrument is available to everybody in the astronomical community. We are expecting that NASA completes the airborne observatory, so that you can use *FIFI LS*, and all the first light instruments can return the investments made by returning exciting infrared data with unprecedented sensitivity and resolution.

REFERENCES

1. E. F. Erickson, "SOFIA: The Next Generation Airborne Observatory," *Space Science Reviews* **74**, pp. 91–100, Nov. 1995.
2. N. Geis, A. Poglitsch, W. Raab, D. Rosenthal, G. Kettenring, and J. Beeman, "FIFI LS: a field-imaging far-infrared line spectrometer for SOFIA," in *Infrared Astronomical Instrumentation*, A. Fowler, ed., *Proc. SPIE* **3354**, pp. 973–985, 1998.
3. W. Raab, N. Geis, A. Poglitsch, D. Rosenthal, A. Urban, T. Henning, and J. Beeman, "The Field-Imaging Far-Infrared Line Spectrometer FIFI LS," in *Infrared Spaceborne Remote Sensing VII*, M. Strojnik and B. Andresen, eds., *Proc. SPIE* **3759**, pp. 86–96, 1999.
4. L. Looney, N. Geis, R. Genzel, W. Park, A. Poglitsch, W. Raab, D. Rosenthal, and A. Urban, "Realizing 3D spectral imaging in the far-infrared: FIFI LS," in *Airborne Telescope Systems*, R. Melugin and H. Röser, eds., *Proc. SPIE* **4014**, pp. 14–22, 2000.
5. L. Looney, W. Raab, A. Poglitsch, N. Geis, D. Rosenthal, R. Hönle, R. Klein, F. Fumi, R. Genzel, and T. Henning, "FIFI LS: a Far-Infrared 3D Spectral Imager for SOFIA," in *Airborne Telescope Systems II*, R. Melugin and H. Röser, eds., *Proc. SPIE* **4857**, pp. 47–55, 2002.
6. W. Raab, A. Poglitsch, L. W. Looney, R. Klein, N. Geis, R. Hoenle, W. Viehhauser, R. Genzel, M. Hamidouche, T. Henning, and E. E. Haller, "FIFI LS: the far-infrared integral field spectrometer for SOFIA," in *Ground-based Instrumentation for Astronomy, Proc. SPIE*, A. F. M. Moorwood and M. Iye, eds., **5492**, pp. 1074–1085, Sept. 2004.

7. W. Raab *et al.*, “Characterizing the system performace of fifi ls: the field-imaging far-infrared line spectrometer for sofia.” To appear in: Ground-based and Airborne Instrumentation for Astronomy, Proc. SPIE, 2006.
8. D. Rosenthal, J. Beeman, N. Geis, L. Looney, A. Poglitsch, W. Park, W. Raab, and A. Urban, “16×25 Ge:Ga detector arrays for FIFI LS,” in *Airborne Telescope Systems*, R. Melugin and H. Röser, eds., *Proc. SPIE* **4014**, pp. 156–163, 2000.
9. A. Poglitsch, R. Katterloher, R. Hönle, J. Beeman, E. Haller, H. Richter, U. Grözinger, N. Haegel, and A. Krabbe, “Far-Infrared Photoconductor Arrays for Herschel and SOFIA,” in *Millimeter and Submillimeter Detectors for Astronomy*, T. Phillips and J. Zmuidzinas, eds., *Proc. SPIE* **4855**, pp. 115–128, 2002.
10. W. Raab, L. Looney, A. Poglitsch, N. Geis, R. Hönle, D. Rosenthal, and R. Genzel, “FIFI LS: the optical design and diffraction analysis,” in *Airborne Telescope Systems II*, R. Melugin and H. Röser, eds., *Proc. SPIE* **4857**, pp. 166–174, 2002.
11. L. Looney, W. Raab, A. Poglitsch, and N. Geis, “Realizing Integral Field Spectroscopy in the Far-Infrared,” *ApJ* **597**, pp. 628–643, 2003.
12. G. J. Stacey, J. W. Beeman, E. E. Haller, N. Geis, A. Poglitsch, and M. Rumitz, “Stressed and unstressed Ge:Ga detector arrays for airborne astronomy,” *International Journal of Infrared and Millimeter Waves* **13**, pp. 1689–1707, Nov. 1992.
13. J. W. Beeman and E. E. Haller, “Ge:Ga photoconductor arrays: Design considerations and quantitative analysis of prototype single pixels,” *Infrared Physics and Technology* **35**, pp. 827–836, Dec. 1994.
14. Y. Creten, O. Charlier, P. Merken, J. Putzeys, and C. van Hoof, “A 4.2 K readout channel in a standard 0.7 μm CMOS process for a photoconductor array camera,” *Journal de Physique IV* **12**, pp. 203–206, 2002.
15. A. Poglitsch, C. Waelkens, and N. Geis, “The Photoconductor Array Camera & Spectrometer (PACS) for the Far Infrared and Submillimetre Telescope (FIRST),” in *UV, Optical, and IR Space Telescopes and Instruments*, J. Breckinridge and P. Jakobsen, eds., *Proc. SPIE* **4013**, pp. 221–232, 2000.
16. R. Klein, A. Poglitsch, F. Fumi, N. Geis, M. Hamidouche, R. Hoenle, L. Looney, W. Raab, and W. Viehhauser, “Real-time operation without a real-time operating system for instrument control and data acquisition,” in *Optical, Infrared, and Millimeter Space Telescopes, Proc. SPIE*, H. Lewis and G. Raffi, eds., **5496**, pp. 138–145, Sept. 2004.
17. C. Kramer, C. G. Degiacomi, U. U. Graf, R. E. Hills, M. Miller, R. Schieder, N. Schneider, J. Stutzki, and G. F. Winnewisser, “New KOSMA 3-m telescope,” in *Advanced Technology MMW, Radio, and Terahertz Telescopes, Proc. SPIE*, T. G. Phillips, ed., **3357**, pp. 711–720, July 1998.