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SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

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ABSTRACT

Coupling a high-contrast imaging instrument to a high-resolution spectrograph has the potential to enable the most detailed characterization of exoplanet atmospheres, including spin measurements and Doppler mapping. The high-contrast imaging system serves as a spatial filter to separate the light from the star and the planet while the high-resolution spectrograph acts as a spectral filter, which differentiates between features in the stellar and planetary spectra. The Keck Planet Imager and Characterizer (KPIC) located downstream from the current W. M. Keck II adaptive optics (AO) system will contain a fiber injection unit (FIU) combining a high-contrast imaging system and a fiber feed to Keck's high resolution infrared spectrograph NIRSPEC. Resolved thermal emission from known young giant exoplanets will be injected into a single-mode fiber linked to NIRSPEC, thereby allowing the spectral characterization of their atmospheres. Moreover, the resolution of NIRSPEC ($R = 37,500$ after upgrade) is high enough to enable spin measurements and Doppler imaging of atmospheric weather phenomenon. The module was integrated at Caltech and shipped to Hawaii at the beginning of 2018 and is currently undergoing characterization. Its transfer to Keck is planned in September and first on-sky tests sometime in December.

Keywords: Adaptive Optics, High contrast imaging, High resolution spectroscopy, Exoplanet characterization, Doppler imaging

1. KECK PLANET IMAGER AND CHARACTERIZER

The Keck Planet Imager and Characterizer (KPIC Ref. 1) consists of an upgrade to the Keck II AO system and instrument suite. The key goal of KPIC is to suppress the starlight and feed the faint exoplanet light into a single mode fiber in order to spectrally characterize the planetary companion using the high resolution spectrograph (HRS), NIRSPEC. Fig.1 shows a block diagram of the KPIC instrument.

KPIC features an avalanche photodiode-based infrared Pyramid wavefront sensor (IR PyWFS), a Boston Micromachines Corporation (BMC) high-order deformable mirror (HODM), a coronagraph, a fiber-injection unit (FIU), a bundle of single mode fibers and a fiber extraction unit (FEU). The HODM, the coronagraph and the FIU are implemented on a optical board called the "FIU plate" while the IR-PyWFS has its own optical board. Both plates will be implemented on the Keck AO bench. The FIU is connected to the FEU located inside NIRSPEC *via* a bundle of single mode fibers. Our plan is to implement the FIU in two phases, requiring two different units. The first FIU plate is a fast-track prototype which will not include the HODM and the coronagraph. The intended use for the FIU prototype is to send a test particle to Keck in order to learn about

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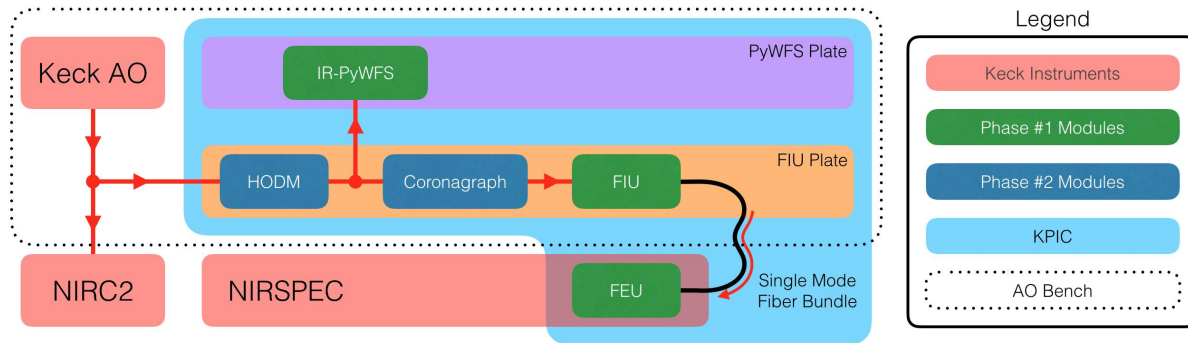


Figure 1. Block diagram of KPIC. HODM - High order DM, FIU - fiber injection unit, IR-PyWFS - infrared pyramid wavefront sensor, FEU - fiber extraction unit.

and optimize sub-system and operational interfaces. A second iteration of the FIU including the HODM and coronagraph is currently being designed and is expected to trail the first plate by six to twelve months.

The infrared pyramid wavefront sensor and the fiber injection unit of KPIC successfully passed a preliminary design review (PDR) in March 2017. Long-lead items such as the off-axis parabolas, tip-tilt mirror, and tracking camera were ordered immediately following the PDR. The design described during the PDR was summarized in Ref. 2 and has been improved upon before successfully passing the detailed design review (DDR) in November 2017. After the DDR, the remainder of the parts were ordered. Once all critical items were received, the FIU module was built and aligned at Caltech before it was shipped to Hawaii in April 2018. In parallel, the pyramid wavefront sensor plate was built and aligned at the Institute for Astronomy of Hilo (IFA). The FIU and PyWFS plates were co-aligned in April, and tested and characterized at the IFA. The final design of the FIU is presented in Sect. 2 and the main results of its characterization are presented in Sect. 3. For more information about the KPIC (requirements, science goals...) consult Ref. 2 and for the IR-PyWFS consult C.Z. Bond paper in this proceeding.

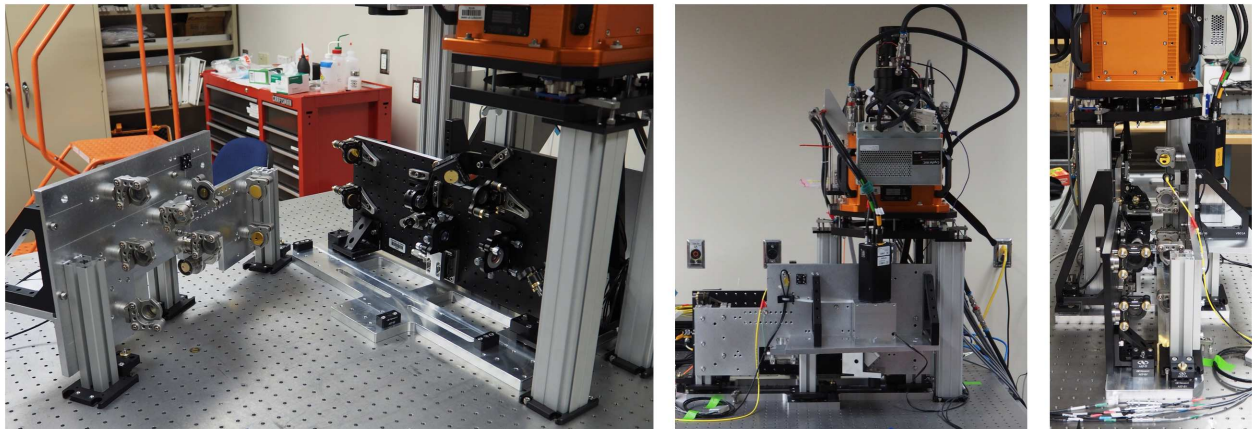


Figure 2. Left: FIU plate (silver) in front of the PyWFS plate (Black). Middle: picture of KPIC from the back side of the FIU plate. Right: Picture of the space between the two plates when co-aligned.

Fig. 2 shows pictures of KPIC in the IFA laboratory. The only part not aligned yet is the fiber port describe in Sect. 2.3. This part will be use to connect the bundle of single mode fiber (Sect. 2.4) to the FIU. The output end of the bundle will be connected to the FEU. This module has already been aligned and tested. Implemented into NIRSPEC in July 2018, it will be used to relay the light from the output of the fiber bundle onto the slit of the spectrograph.

2. FIBER INJECTION UNIT VERSION ONE: FINAL DESIGN

The final design of the first version of the FIU plate is shown in Fig. 3. The FIU optical design is based on off-axis parabolas (OAP) arranged in a double symmetric F/15 relay (left image). The first relay is designed to accommodate a Boston MicroMachines Corporation 34x34 actuators, 3.5 μm stroke deformable mirror, and a beamsplitter sending the light to the IR PyWFS (90% of J and H bands). The second relay is designed to accommodate a reflective pupil apodizer and a possible focal plane coronagraphic mask. The deformable mirror and the coronagraph modules will be implemented during the second phase. A fifth OAP is used to collimate the beam and feed the FIU. In this module, visible on the right image, the light is reflected by a tip-tilt mirror in the direction of a dichroic dividing the light into two beams. The first one is focused on the tracking camera by several lenses and the second one on the fiber bundle by an OAP. The image formed on the tracking camera allows for the star position to be determined, which will be used to guide on while spectroscopy of the known exoplanet is underway. The lens located in front of the detector is mounted on a motorized translation stage. By removing this lens we can image the pupil plane.

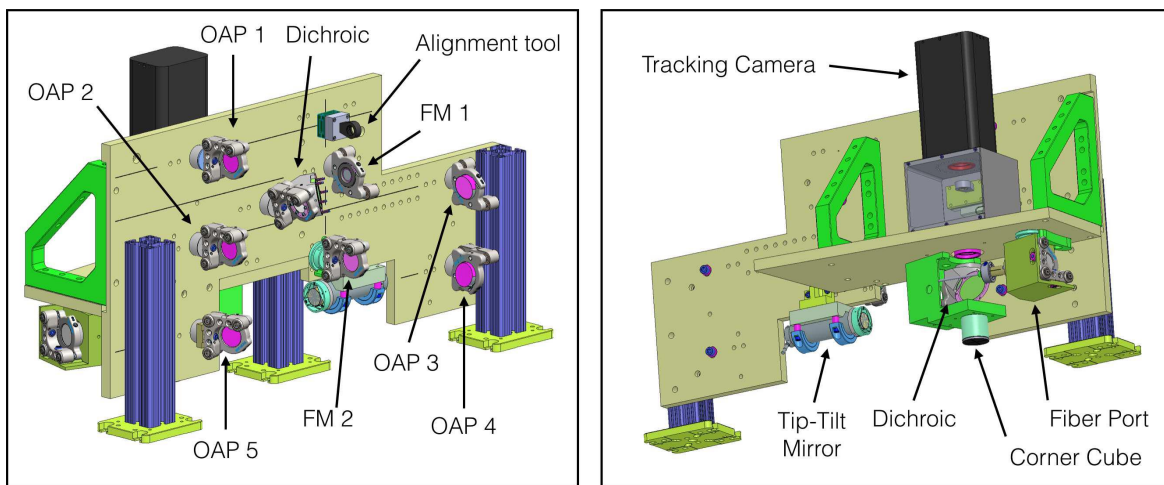


Figure 3. Left: front view of the FIU plate. Right: back view of KPIC where the FIU is visible.

The input connector of the fiber bundle contains five science fibers and 6 calibration fibers (Sect. 2.4). To determine the relative position of the fibers in the bundle to the star/planet, four calibration fibers in the bundle are retro-fed by a laser source (1550 nm). This light, collimated by the OAP in front of the bundle, is reflected by the dichroic and by the corner cube before going through the dichroic onto the tracking camera. Assuming the relative position of each fiber of the bundle is calibrated a priori, one can determine the position of the star/planet with respect to the fibers. In addition, two other calibration fibers are connected to a photodiode (one per fiber). Using the tip-tilt mirror, we can move the image of the star in both detector and fiber bundle planes to determine precisely where the two calibration fibers are by optimizing the flux coupled into them and finally deduce the position of the science fibers. To inject the planet light into the fiber, we use the tip-tilt mirror to move the planet to the position of one of the five science. In order to properly reduce the data, two of the science fibers are allocated to monitoring the starlight and sky background.

2.1 Tip-tilt mirror

The tip-tilt mirror is used to move the science target on the fiber array and track the planet over time. We chose a strain-gauge closed-loop control fast steering stage from the S-330 series from Physik Instrumente. This stage satisfies our requirement on the patrol field (off-axis planet fiber patrol area) and tracking accuracy requirements. Instead of gluing the flat mirror directly to the stage, we decided to use a custom made fixation shown in Fig. 4. Designed to minimize the stress applied to the flat mirror, this removable fixation will be redesigned, in the second phase of the project, to accommodate a reflective Lyot stop.

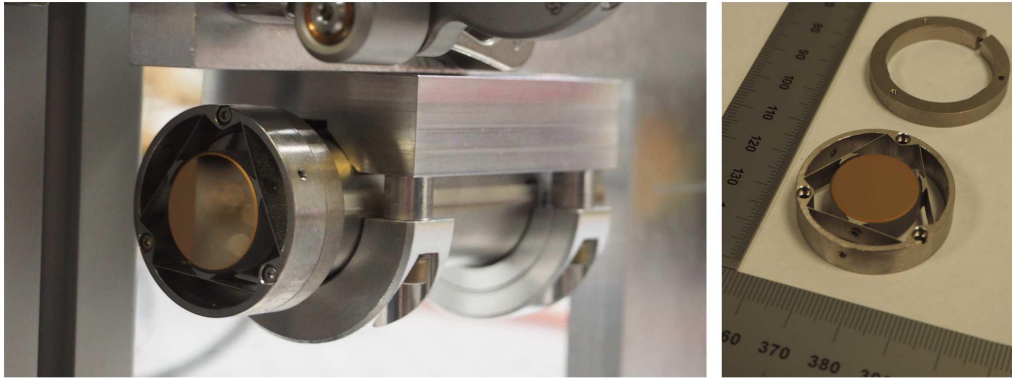


Figure 4. Left: picture of the tip-tilt mirror mounted on the FIU plate. Right: picture of the custom made fixation.

2.2 Tracking camera

The tracking camera is a C-RED2 from First Light Imaging (FLI) able to operate at both J and H bands. The C-RED 2 is a 640x512 InGaAs camera with the following characteristics: InGaAs 640 x 512 PIN Photodiode sensor, $0.9\ \mu\text{m}$ to $1.7\ \mu\text{m}$, 70% quantum efficiency, $15\ \mu\text{m}$ pixel pitch, windowing and ROI modes available, TE3 cooled sensor operation for low dark current. The camera can provide very low read noise ($< 30\ e^-$) and dark current ($100\ e^-/\text{pixel}/s$) at high frame rates (up to 600 Hz full frame). The camera is also compact, which integrates well in our tight operating space constraints.

2.3 Fiber port

The first version of the FIU plate contains one fiber port. This custom part shown in Fig. 5, contains an off-axis parabola (OAP) in a three-axis mount and a connector for the fiber bundle described in the next paragraph. The focal length of the OAP, 35 mm, is optimized to maximize the light injection into the fiber of the bundle. The theoretical injection computed is better than 62% in K and L bands.

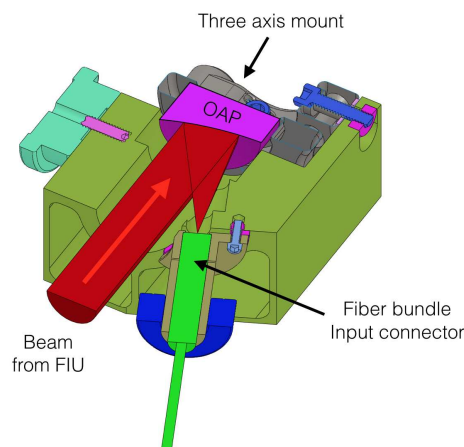


Figure 5. Left: cross section of the fiber port used by the first version of the FIU plate. Right: picture of the fiber port with the dummy bundle used during the mechanical tests.

2.4 Fiber Bundle

Fig. 6 presents a schematic diagram of the first fiber bundle used to connect KPIC to NIRSPEC. This fiber bundle contains two kind of fibers: off-the-shelf fluoride fibers manufactured by Le Verre Fluoré (ZBLAN 6.5) and silica fibers manufactured by Corning (SMF-28-J9). On both input and output connectors of the bundle, dummy fibers are used to fill in the gaps between active fibers during the manufacturing process. The fluoride fibers used as science fibers offer a single mode cut-off at $1.95\ \mu\text{m}$. The attenuation of this fiber in H band is lower than $5.3\ \text{dB/km}$ (transmission $>99\%/m$) and lower than $350\ \text{dB/km}$ (transmission $>92.2\%/m$) in L band.

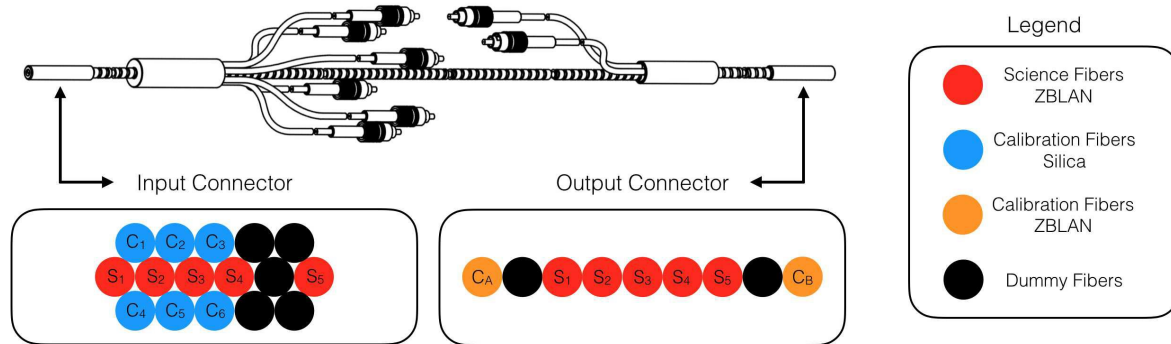


Figure 6. Diagram of the first fiber bundle designed and manufactured for KPIC.

In the input side, which connects to the FIU, five of the ZBLAN fibers, six silica fibers and five dummy fibers are butted against each other cladding to cladding. In this configuration, the cores of the fibers are separated by $125\ \mu\text{m}$ which corresponds to an angular separation of $0.89\ \text{arcsecond}$ on sky. The six silica fibers marked in blue will be used to align the bundle with respect to the star/planet system. Four of them will be retro-fed by a laser diode ($1550\ \text{nm}$) and two will be connected to a photodiode (one for each fiber).

The ZBLAN fibers marked in red will be used for science. Their outputs end are part of the output connector (right) connected to NIRSPEC. In this connector, the five fibers are also cladding to cladding. They are aligned to illuminate the slit of the spectrometer. The two ZBLAN fibers marked in orange will be fed by two broad band light source and used to align the bundle with respect to the slit of NIRSPEC.

Fig. 7 presents a picture of the first bundle manufactured by FiberGuide Industries. Received in May, it will be characterized at Caltech in July before it is connected to the FIU plate and tested.

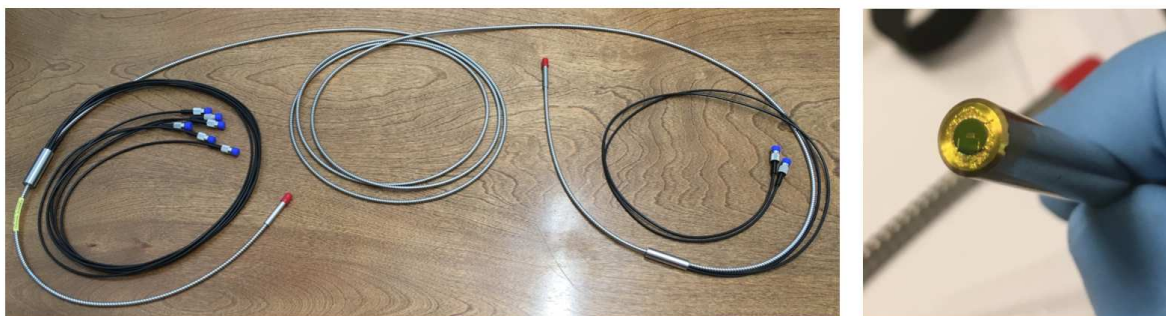


Figure 7. Left: picture of the first bundle manufactured by FiberGuide Industries. Right: picture of the input connector.

3. CHARACTERIZATION

The FIU plate and all its components were characterized during the alignment procedure and once more when integrated with the PyWFS plate. The characterization included a series of tests, among them:

- Individual characterization of each component: OAP, flat mirrors, dichroics, tip-tilt mirror, translation stage...
- Throughput – We measured the throughput of the FIU plate at 1550 nm using a power meter. The throughput's obtained were close to expectation. However, the goal of the fiber injection unit is to inject K and L bands light into the fiber which could not easily be measured in the laboratory. This test will therefore be repeated for these longer wavelengths once the last OAP and the fiber bundle are installed.
- Wavefront error – We measured the wavefront error up to the tip-tilt mirror (included) using a Zygo interferometer (< 30 nm RMS). We also estimate the wavefront error up to the tracking camera using the images registered by the detector. The end-to-end wavefront error between the FIU input and the fiber bundle will be measured when the last OAP and the fiber bundle will be aligned.
- Stability test – We measured the deviation of the PSF registered by the tracking camera over a long period of time (60 hours). During this experiment, we also registered the temperature and the humidity in the laboratory. Fig.8 presents the results obtained during this test.

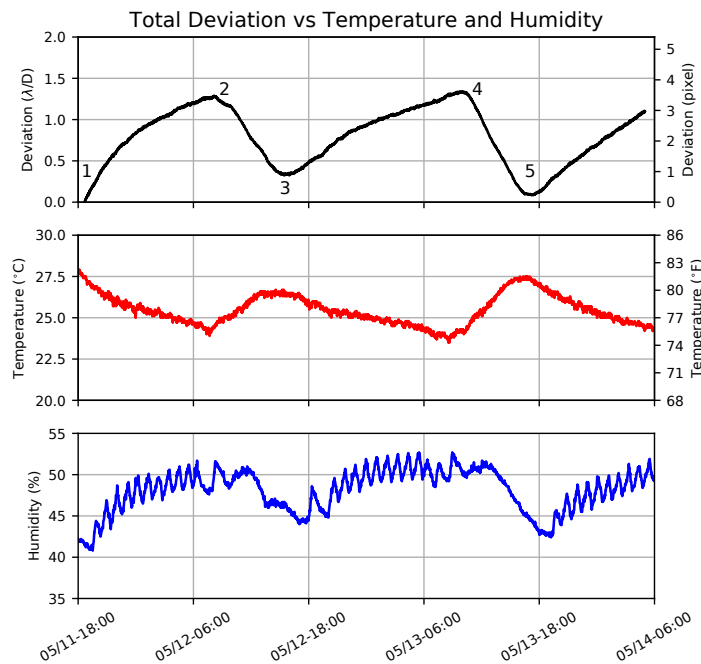


Figure 8. PSF deviation (top), temperature (middle) and humidity (bottom) registered during the stability test.

We can observe a strong correlation between the deviation of the PSF and the variation of the temperature. We estimate the deviation at $0.3 \lambda/D$ per $^{\circ}C$. Because the temperature of the Keck AO room is around $0^{\circ}C$, it will probably be necessary to adjust the alignment of the FIU plate at the summit. Once the fiber bundle is aligned, it will be useful to determine if the position of the fiber bundle with respect to the tracking camera evolves as a function of the temperature. If it does, it will be mandatory to correct this effect with the tip-tilt mirror to optimize the planet light injection into the fiber.

- Co-alignment repeatability – Both plates sit on a common base visible in Fig. 2. A kinematic interface between the base and each plate have been designed to be able to remove both plates independently. Because KPIC will be moved several times and upgraded, it is an important functionality. Numerous tests have shown that removing one of the plates or both from the kinematic base does not affect the alignment of KPIC. The PSF shift registered by the tracking camera and the aberrations measured by the PyWFS are mostly small tip-tilt aberrations. They can easily be compensated by using the tip-tilt steering mirror on the FIU plate and by the pyramid modulator on the PyWFS plate.

Before transferring KPIC to the Keck II Telescope in September, we need to perform all the tests related to the fiber bundle, characterize the detector properly which was recently upgraded and finalize the reduction of the data obtained.

4. CONCLUSION

In this proceeding, we presented the final design of the first fiber injection unit plate and its status. We decided to build the FIU in two stages, based on the same double relay concept. The first version has been integrated at Caltech, shipped to the IfA and co-aligned with the PyWFS plate. Its characterization started in April and is almost completed. During the next two months the fiber bundle will be characterized at Caltech, shipped to the IfA and integrated with the FIU. Then the full system will be tested before it is transferred to Keck in order to prepare for first light, planned in December.

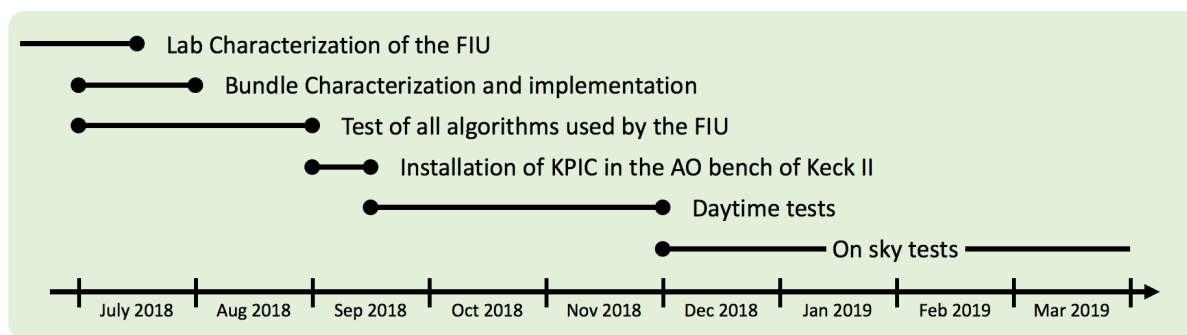


Figure 9. Schedule of the FIU for the next few months.

In parallel, a second FIU plate will be built, mostly identical to the first one but equipped with a deformable mirror and coronagraph module. We expect the second plate to be ready in spring 2019 before being shipped and commissioned at Keck Observatory in 2019.

ACKNOWLEDGMENTS

The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The near-infrared pyramid wavefront sensor is supported by the National Science Foundation under Grant No. AST-1611623. The fiber injection unit is supported by the Heising-Simons Foundation. The PWS camera was provided by Don Hall as part of his National Science Foundation funding under Grant No. AST 1106391.

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