# P07: Summary of PFS Engineering Observations in FY 2022

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**Abstract:** In FY2022, Prime Focus Spectrograph (PFS) completed five engineering observation runs as of January. The biggest achievement in them must be the engineering first light using the end-to-end optical path of PFS with Spectrograph Module 1 (SM1) in September. 470 science grade optical fibers are successfully positioned on the target stars in a field of NGC1980 on the primary focal plane of Subaru Telescope, and spectra were observed at once in the blue (380-650um) arm and the red (630-970um) arm, with the spectra of twenty flux calibration standard stars. Besides, auto guiding (AG) loops using PFS AG cameras and telescope control via Gen2 were successfully closed with errors less than 0.1 arcsec. This was the last step just before proceeding to the final tests using the Telescope AG system. The key performances of PFS were also examined. Convergence precision and speed of the fiber positioning modules Cobras showed good stability in the repeated convergence processes. The spectroscopic data are under analyses to characterize spectrum traces on detectors, wavelength calibration with arc lamp spectra, throughputs with flux standard star spectra, and so on. Newly developed Gen2 commands supported operations of those measurements. Through the engineering run in FY2022, we also found some issues such as the focal position difference between AG cameras and the science fiber tips with 0.55-0.60mm. Finer tuning of the fiber positioning process is also necessary for maximizing the observation efficiency. In FY2023, PFS collaboration will keep tackling those issues, besides the NIR camera integration, for realization of the science operation.

## Key performance and characteristics

### 1. Cobra convergence stability

Cobra convergence is an ability of the fiber positioners "Cobras" to reach to commanded positions accurately and quickly. We measured the convergence through runs every time we set Cobras to designed positions. The number of trials with designs for real sky objects would reach to more than one hundred times in total, in addition to the intensive test with non-sky-object designs in test purpose.

In most of the cases, more than 95% Cobras reached to the positions within 10 iterations in several minutes with the convergence threshold of 10 um, which is sufficient for science operation. Note that the rest 5% includes un-assigned.

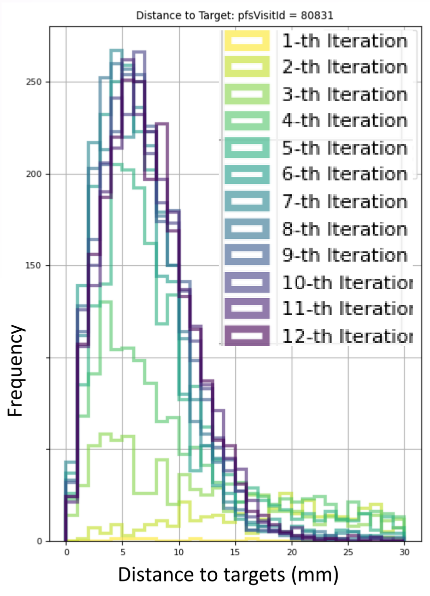



**Figure 1:** An instance of Cobra convergence. This figure shows the histograms of fibers against their distance from the designated position over iteration. (In courtesy of Yan et al.)

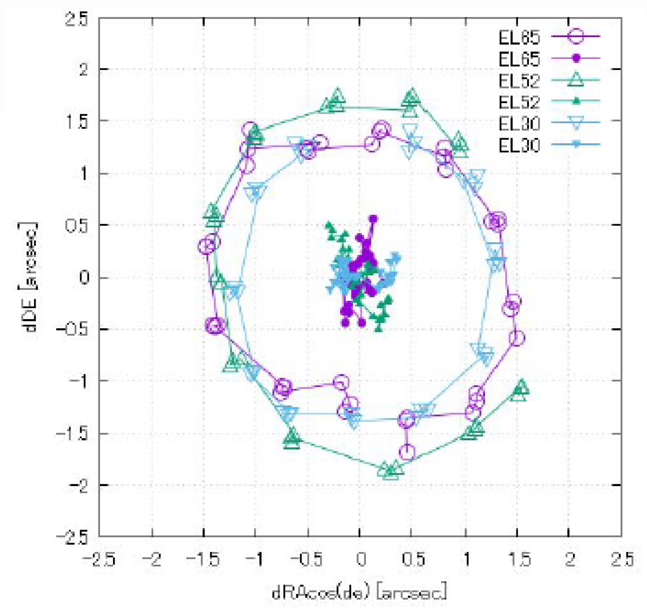



**Figure 2:** Measurement of the difference between the instrument rotator center and the telescope pointing axis. Residuals of the actual star position on AG camera from the expected position in various rotator angles are plotted on RA and Dec plain. This measurement was repeated with telescope elevations of 30, 52, and 65 degrees. (In courtesy of Kawanomoto et al.)

### 2. PFI position repeatability

Repeatability of the PFI position over installation to and removal from the telescope was estimated. The variation of the PFI rotator center between Run 6 and Run7, measured from the telescope pointing errors calculated with stars on AG cameras in various instrument rotator positions, was 41 um. The PFI position variation stayed within the requirement on the PFI position variation introduced by its installation to and removal from POpt2, which is 200 um in lateral direction against the optical axis of the telescope primary mirror. It was also assured from the PFI rotator center position measured with MCS that the PFI position measured in Run 8 was consistent with the previous ones in 2019 and 2021.

### 3. "Dot" position measurement

PFI Field Element has dots in the same number of science fibers printed on its surface. They are used for masking fibers around a bright light source to prevent light contamination to neighbor fibers on detectors.

Exact positions of the dots were measured through Run 7 and 8 by moving Cobras along theta- and phi-axes step by step while observing their locus by MCS. By knowing the actual position of dots on PFI plain, more precise control of Cobras to mask them behind dots became possible. This technique is to measure spectrum traces on detectors precisely. Also, it could be used to observe the defocused PSFs on spectrographs' detectors in purpose of the research on PSF modeling.

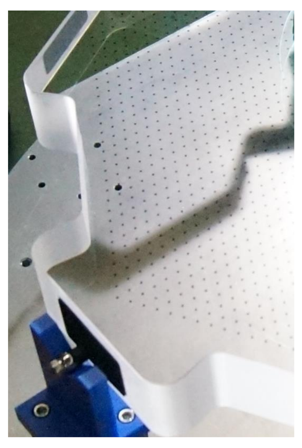


**Figure 3:** Dots printed on the PFI field element. The field element is installed right in front of science fiber tips.

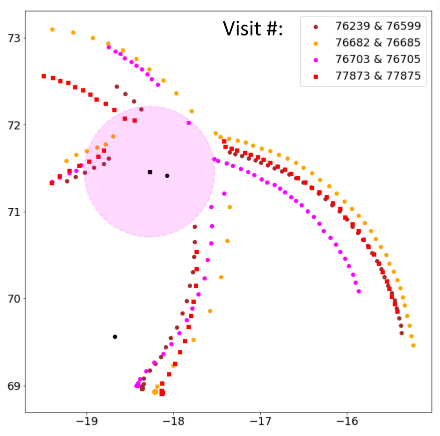



**Figure 4:** An example of the dot position measurement with an MCS image. Each small dots shows the locus of fibers, and large pink disk shows the measured dot position. (In courtesy of Neven et al.)

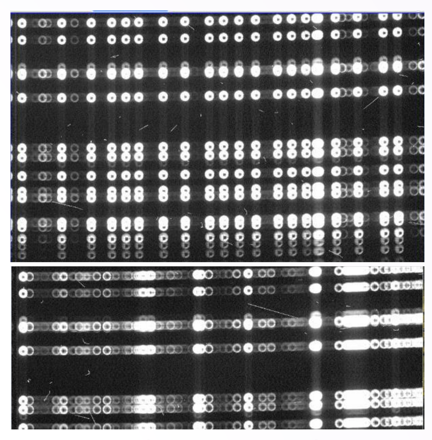
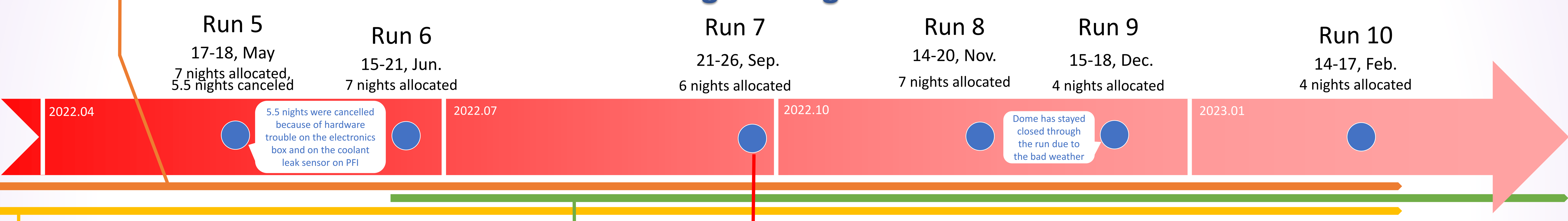


**Figure 5:** Defocused images of emission lines on a spectrograph's detector with fibers hidden behind "dots" (top) and without the hidden fibers (bottom). (In courtesy of Neven, Le Fur et al.)

## Timeline of PFS engineering observation in FY2022




## Sky-PFI coordinate transformation

In Run 6, it is found that the targets on sky were apart from science fibers with 1-2 mm shift on PFI plain and about 1 deg rotation after Cobra convergence to a designed configuration. The cause of the offset was pursued with raster scan, a newly developed function for this purpose (Takagi, Arai, Koshida et al. ), on defocused bright star images.

After investigations on the coordinate transformation used in the Cobra convergence, it turned out that MCS-PFI transformation employed the designed positions of the fiducial fibers (FF) while sky-PFI transformation employed the measured positions by scanner in laboratory. The discrepancy introduced difference of Cobra center positions as big as 3mm. It explained the large part of the Cobra offsets.

By correcting the discrepancy, Cobras were positioned on sky objects within distances less than 1".5, which led to the successful engineering first light. However, the residual offset still show a systematic pattern similar to the distortion measured by HSC. The amplitude was several time larger in PFI. In future engineering observations, this pattern will be also corrected in the Cobra positioning process.

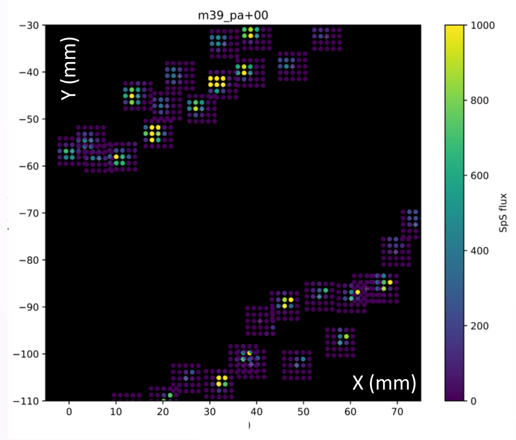



**Figure 6:** An example of the raster scan data visualized on PFI plain. Total flux in a fiber are plotted on each dithered position. (In courtesy of Lupton et al.)

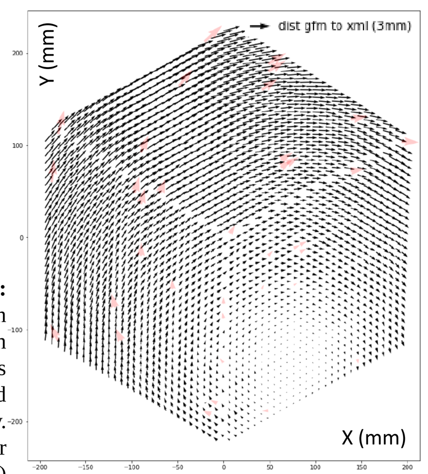



**Figure 7:** Difference between coordinate based on designed FF positions and on ones measured in laboratory. (In courtesy of Le Fur et al.)

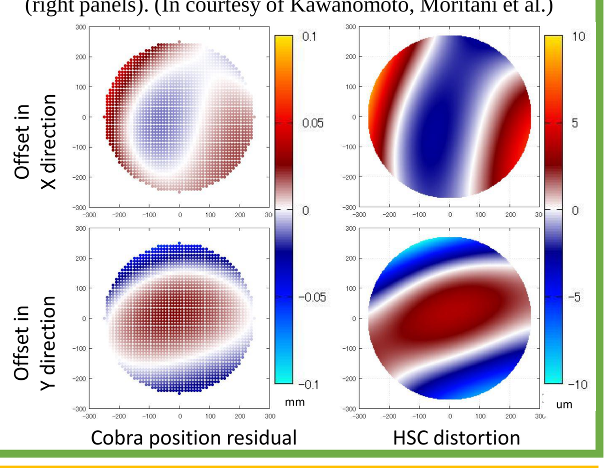



**Figure 8:** Cobra position residuals after correcting coordinate discrepancy (left panels) and distortions measured by HSC (right panels). (In courtesy of Kawanomoto, Moritani et al.)

## Auto-guiding system

In FY2022, PFS auto-guiding (AG) system was proven to be able to close AG loop successfully with the telescope control via Gen2.

PFS AG process flow is illustrated in Figure 9 with some simplification. As other submodules of PFS, AG system consists of software named "Actor" which are assigned to each specified tasks. Actors communicate through Message Hub System, the integrated communication platform for all Actors.

In normal operation, AG error computed by AG Actor is sent to the telescope control system through MLP1. However, this flow was not available in FY2022 because of the function verification by MELCO had to be postponed for about a year due to the hardware trouble happened to PFI in Nov. 2021.

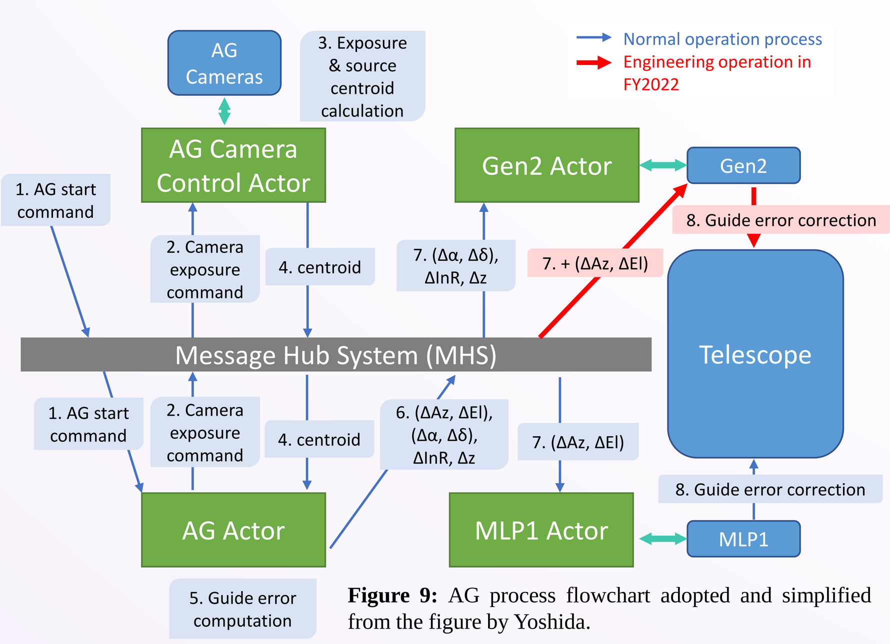



**Figure 9:** AG process flowchart adopted and simplified from the figure by Yoshida.

Instead, an AG error correction system through Gen2 was developed (Jeschke, Yoshida et al. ) and used in engineering observation in FY2022. AG loops were successfully closed with the system with a typical guide error smaller than 0".1 .

Final test of the normal flow using Subaru telescope control system via MLP1 with MELCO is planned in the next engineering run in Feb. 2023.

## Engineering First Light and achievements following

After various efforts for introducing sky objects onto the science fibers, we succeeded in the engineering first light in Run 7. 470 fibers are allocated to stars distributed in a field of NGC 1980, an open cluster in Orion, beside 20 fibers allocated to flux standard stars at the same time.

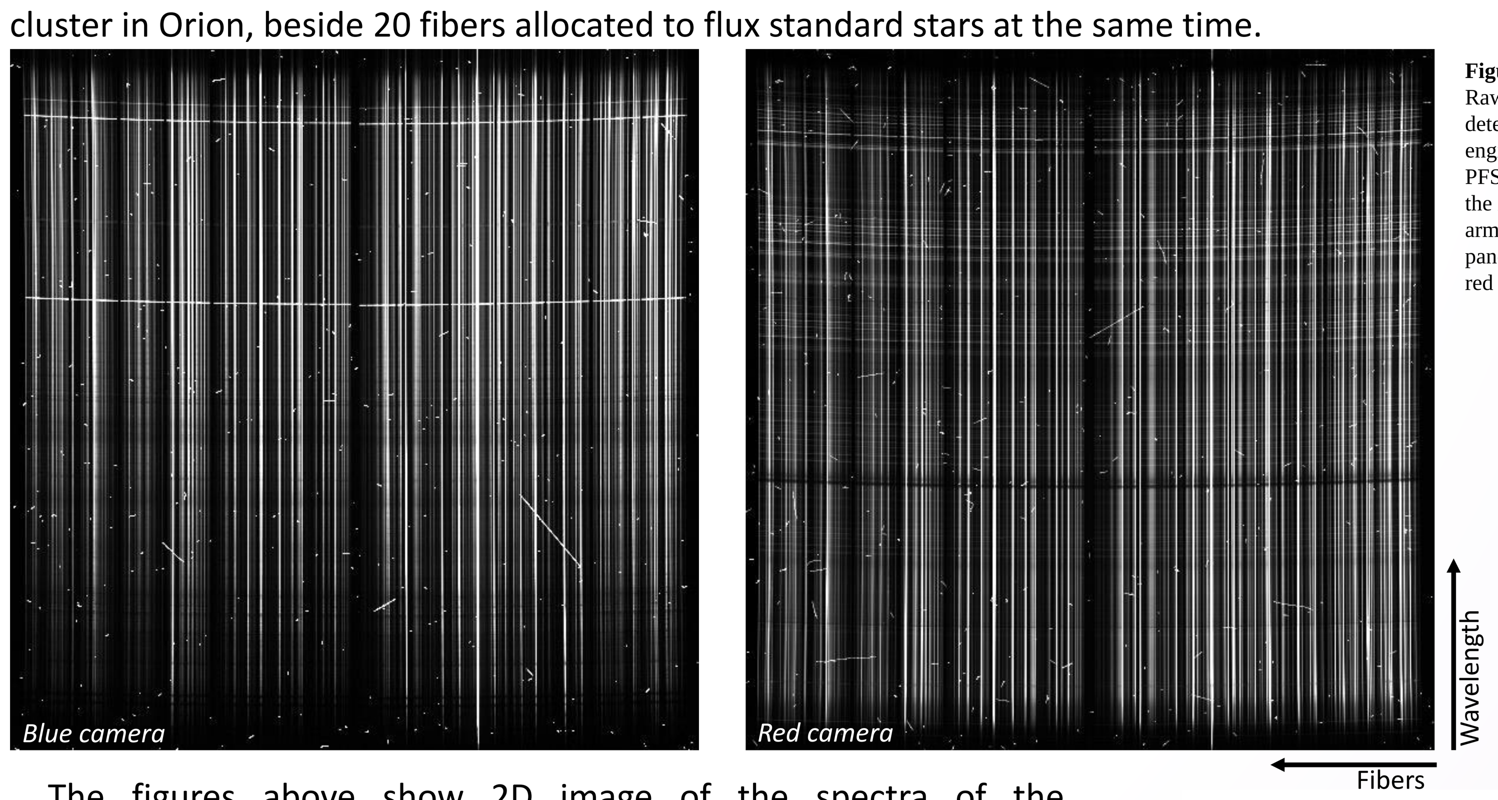



**Figure 10:** Raw spectrograph detector image of the engineering first light of PFS. Left panel shows the image in the blue arm of SM1, while right panes shows one in the red arm.

The figures above show 2D image of the spectra of the engineering first light in the blue and the red arms. Spectra of stars or faint distant galaxies in different fields were also observed in Run 8. In addition, we succeeded in observing sky objects with 600 more fibers in the blue and red arm of the additional spectrograph module, SM3, in the same run.

Data reduction such as sky subtraction, wavelength calibration or flux calibration on these data is ongoing using calibration data taken in the same run such as dome flat images with halogen or arc lamps for spectra traces and wavelength calibration. With preliminary data reduction, we could detect emission lines on a spectrum of a galaxy and could estimate a redshift with 1D pipeline as z ~ 0.83.

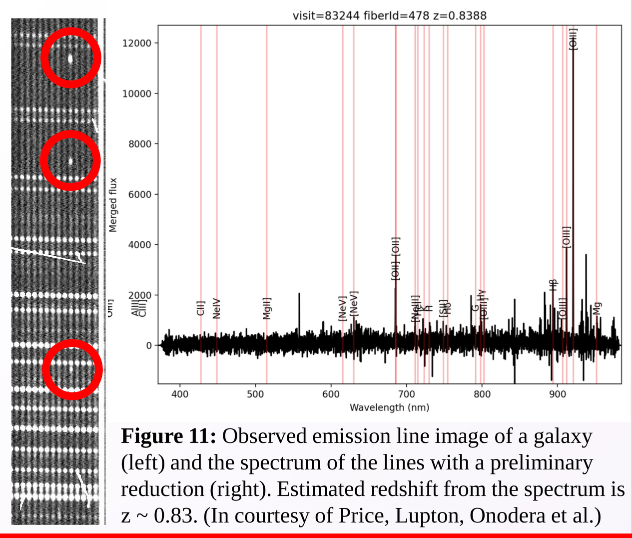


**Figure 11:** Observed emission line image of a galaxy (left) and the spectrum of the lines with a preliminary reduction (right). Estimated redshift from the spectrum is z ~ 0.83. (In courtesy of Price, Lupton, Onodera et al.)

## Future works

One of the important issues to be solved in future is the error in the focal position of cameras, which are 0.56 mm away from the best focus for the science fibers. That was found from the through focus test. This error will be filled by putting additional field elements in front of AG cameras in Feb. 2023.

Besides continuing the finer tuning of fiber positioning as discussed in the sky-PFI coordinate transformation section, PFS hardware installation will be completed in the next FY, starting with the first NIR camera in spring. PFS system performances such as on-sky sensitivity with the full system will be completed in FY2023 before open use of PFS starts in FY2024.

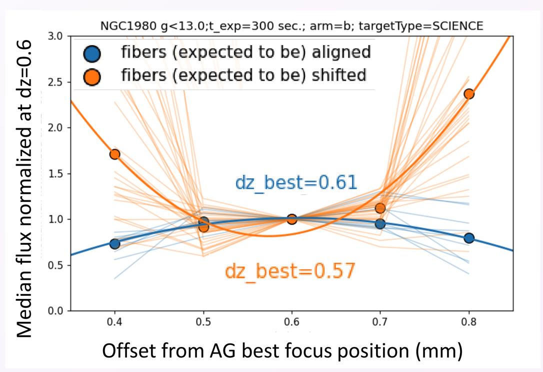



**Figure 12:** Focal position search for science fibers by through-focusing. Both of blue-arm flux variation in fibers aligned on stars (blue symbols) and one in fibers off from stars shows consistent gap around 0.6 mm from the AG best focus position. (In courtesy of Yabe et al.)

**Summary:** PFS experienced 5 engineering observation run by December in FY2022. In spite of difficulties such as the bad weather and the telescope and instrument troubles during those runs, important key performance evaluations were carried out to assure the functions of PFS such as the PFI position repeatability at the primary focus of the telescope, Cobra positioning repeatability, focal positions of AG cameras and science fibers, and so on. Fiber positioning accuracy was dramatically improved by the intense analysis of the repeated raster scan data, obtained by the Gen2 functions newly developed for this purpose. PFS auto-guiding system has been proven to be able to close the guiding loop successfully with telescope control via Gen2. After all those efforts, we achieved the engineering first light in September with the field of NGC1980. Many spectra of stars and galaxies has been taken in the consecutive engineering runs along with calibration data. Data reduction such as sky subtraction, wavelength calibration and flux calibration with the pipeline is under examination with those spectrograph data. In the last run in FY2022, in Feb. 2023, auto-guiding system will be tested and certified to be functional with Subaru telescope control system, as designed. In FY 2023, whole PFS modules will be installed in Subaru, followed by completion of the engineering observation before the open use and SSP with PFS will be started.