Instrument Performance verified through the PFS engineering observations

Yuki Moritani[1,2], Kiyoto Yabe[1,2], Shintaro Koshida[1], Satoshi Kawanomoto[1], Robert Lupton[3], Craig Loomis[3], Arnaud Le Fur[3], Chi-Hung Yan[4], Jennfier Karr[4], Masayuki Tanakai[1] , Miho N. Ishigaki[1], Wanqiu He[1] , Arai Akira[1] , Vera M. Passegger[1] , Ichi Tanaka[1], Jim Gunn[3], Naoyuki Tamuara[1,2], and PFS development team.

1: Subaru Telescope, 2: Kali IPMU, 3: Princeton University, 4: ASIAA

1. Introduction -- PFS commissioning

PFS (Prime Focus Spectrograph, Fig 1)

Powerful instrument
- Wide field (~1.25 deg^2)
- High multiplexity (2394 reconfigurable fibers)
- Wide waveband (380nm-1260nm with three channels)

Engineering Observation/on-telescope test (Fig 2)
- 24 runs (as of October 2025) since 2018
- On-sky test started in Sep. 2021.
- ~160 nights, among which ~40 nights were cancelled due to weather, telescope/instrument trouble.
- The number includes on-telescope test during telescope down time.
- Run with the full-system (i.e. 12 SpS cameras): 2 runs.

Goal of the PFS commissioning
- Validate the instrument functions on-telescope
- Characterize the instruments to put the targets on the fiber, and to process the data.
- Validate the instrument performance
- Stabilize and optimize the performance ← We are here now

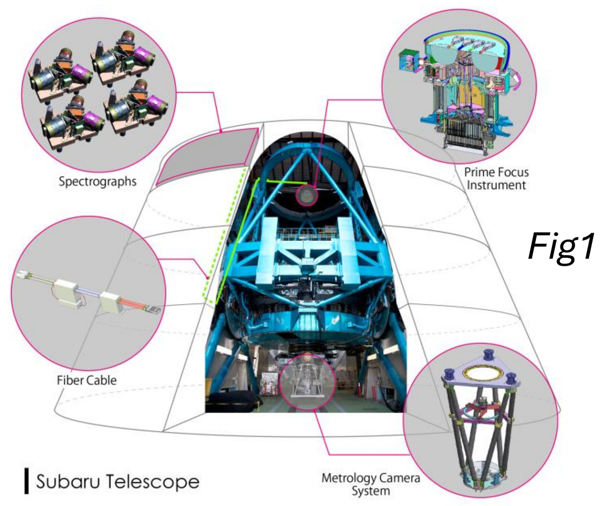


Fig1

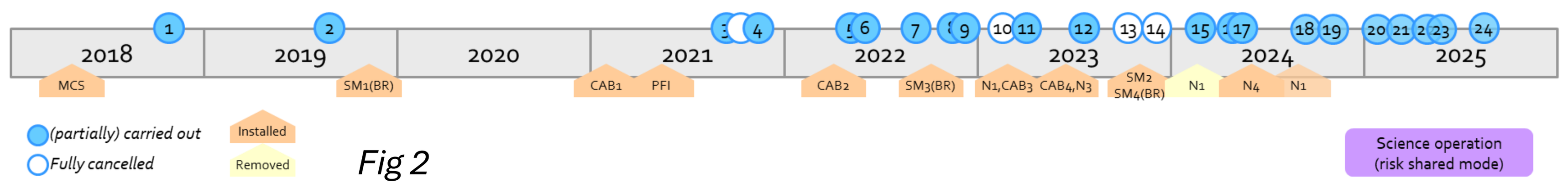


Fig 2

2. Performance 1: Throughput and its variation

Throughput variation in one observing run
- Variation at different time.
  - Timescale : hours, amplitude a few %.
  - Caused by tiny (<1um) change in the air gap between the fiber surface at the connector.
  - When the index matching gel is applied to fiber connectors (Fig 3), the throughput variation is suppressed to be <1%, as long as the fibers at the same position (Fig 4). Results are the same among the runs (Fig 5).

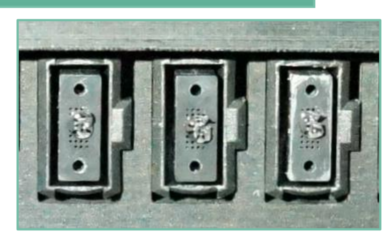

The index matching gel Thorlab G608N3

Fig 3

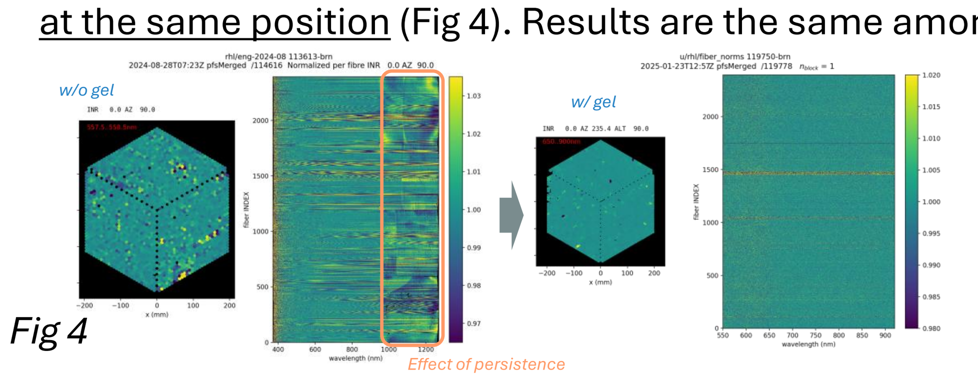


Fig 4

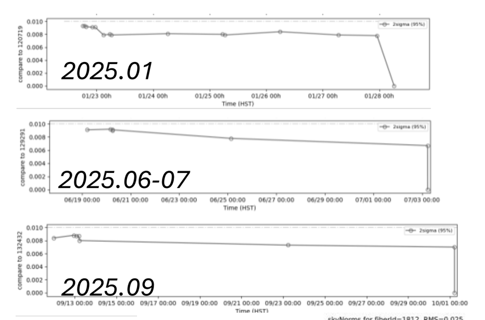


Fig 5

- Variation at different fiber position in the patrol region (Fig 6)
  - Recent data analysis of ~1000 visits revealed that throughput changes by a few % within the fiber patrol region.
  - Caused by bending and misalignment of the fiber positioner axes (theta, phi) w.r.t chief ray.
  - Modeling using motors angles (theta, phi) is being established.
  - Empirical model fits good: the residual is <~0.5% for most of fibers.

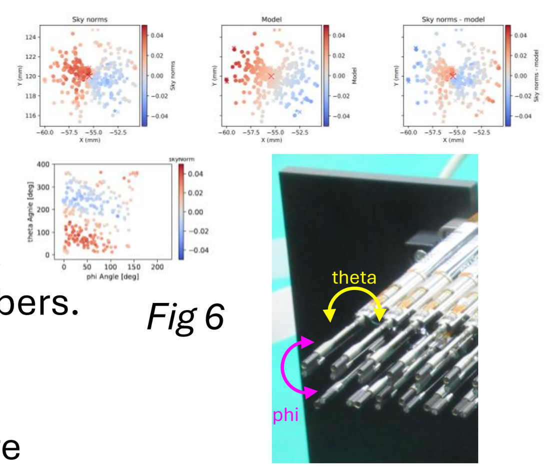
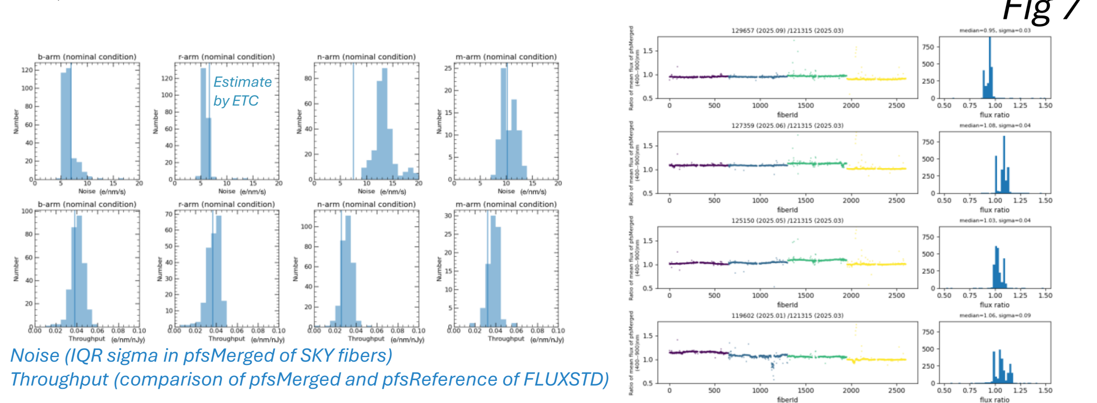


Fig 6

Throughput variation among the runs
- Throughput changes by +/- ~10% run by run (Fi. 7)
  - The fiber connectors between PFI and Cable B on the spider are unplugged and plugged every run, and fiber surface is cleaned

Adjustment of throughput and ETC
- Based on the results in the S25A semester, the throughput model and noise model was updated. (Fig 8)



Noise (IQR sigma in pfsMerged of SKY fibers)
Throughput (comparison of pfsMerged and pfsReference of FLUXSTD)

Fig 7

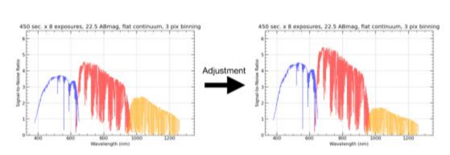


Fig 8

3. Performance 2: Fiber configurations

Fiber "convergence"
- Convergence time
  - 163.6 sec on average (889 convergence from May 2024 to June 2025, runs 16-23)
    - Home + 8 iterations (MCS exposure is 4.8 sec)
  - 134.7 sec on average (394 convergence in September 2025, run 24), moving the fibers to Home during SpS readout.
  - Further improving point: discard the fibers which are far away from the targets at the end of sequence, to reduce the maximum step size.
- Convergence rate: how accurately the fibers are moved to the targets position. Here, the error in target position is assumed to be zero.
  - 7.4 um (75%-tile)/ 143.1 um (95%-tile) on average (1480 convergence sequences from May 2024-September 2025 (runs 16-24)
  - 75% -tile is used for operation, because this metric isn't affected so much by the dome seeing, and it's been stable over years. (Fig 10)
  - However, 95%-tile started increasing in 2025 (Fig 9).
  - With new motor map, the convergence rate improved.
- To recover the convergence, full calibration (resonant frequency, on-time, motor map) of the fiber positioners is underway.
  - The last update was in 2021, when PFI was shipped to Subaru.
  - The geometry data, whose last update was in 2022, are also being updated (Fig 11).

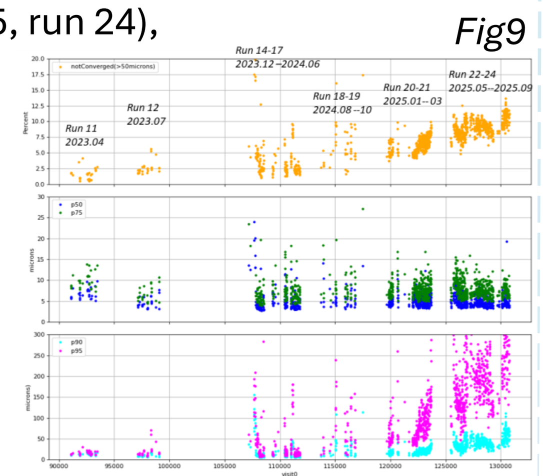


Fig9

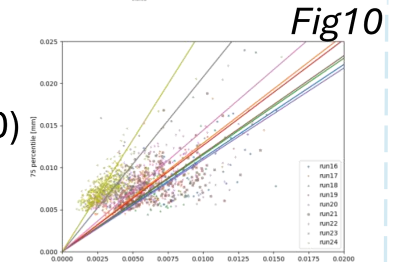


Fig10

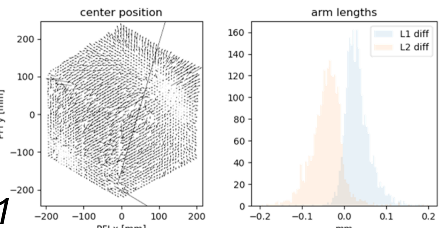


Fig11

Fiber configuration accuracy
- Test with "raster scan" method
  - Move the fibers to the targets (Gaia DR3 stars), and take spectra by dithering the telescope to measure the actual star positions as the flux-weighted average (Fig 12).
- Configuration accuracy: 20~50um as 95%-tile
  - Larger error at lower elevation (Fig 13).
  - Residual shows a "Pattern", repeatable for change in EL.
  - Configuration error dominates the measured flux loss and its non uniformity

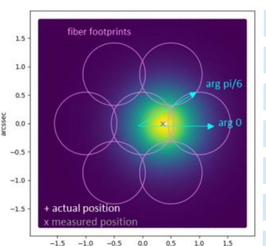


Fig 12

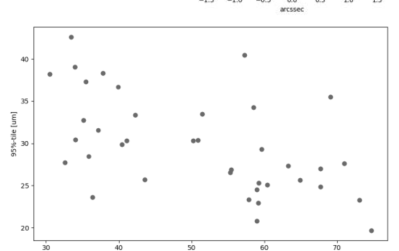


Fig 13

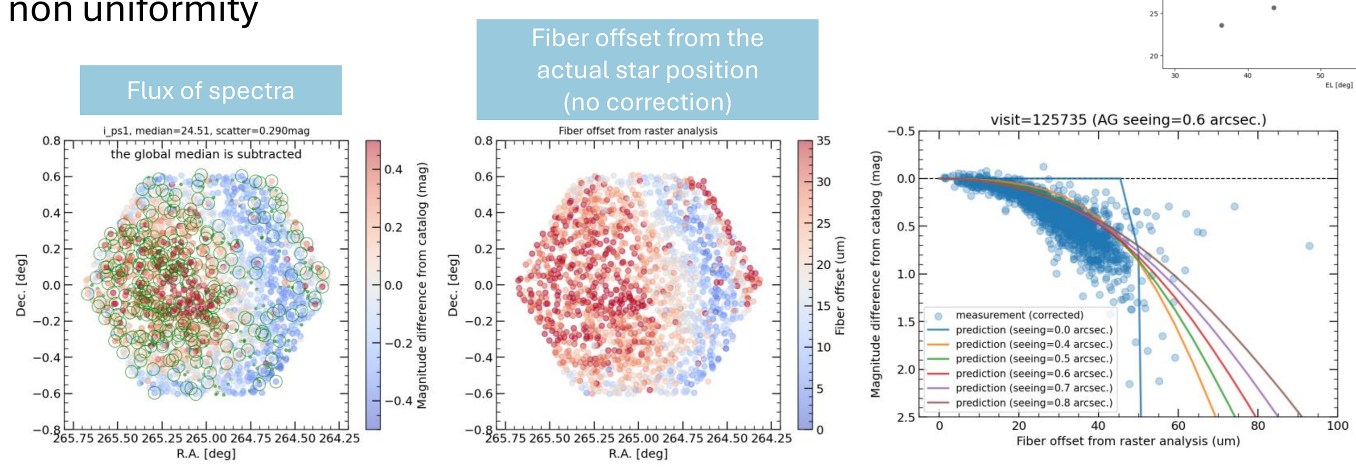


Fig 14

- Convergence software was updated to measure low-order term (global shift, rotation, scale) more robustly.
  - Exclude outliers, as well as avoid collision with FFs
- MCS images were taken at various InR and EL show position shift from EL=90 (Fig 16)
  - Measured fiber position showed a similar pattern to the observed fiber offset.
    - Pattern depends on EL and InR. Both rotating and fixed component exists.
    - Coordinate transformation was updated to keep the fiber position the same at EL<90 (Fig 15).
    - The residual became much smaller, and its pattern looks similar to the rotating component (Fig 17).
  - The next step is to consider the rotating component.

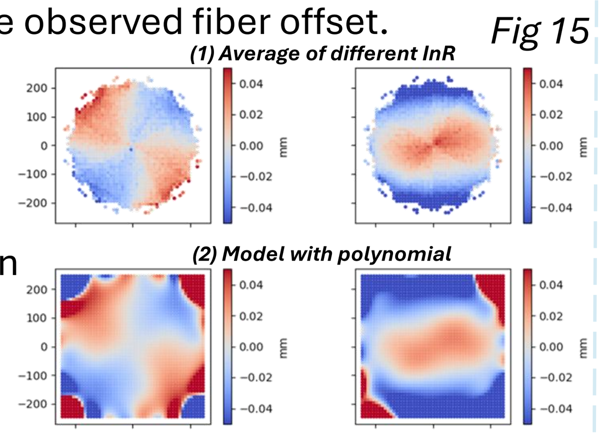


Fig 15

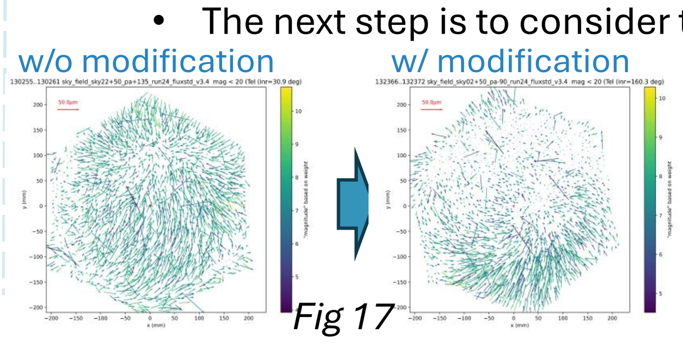


Fig 17

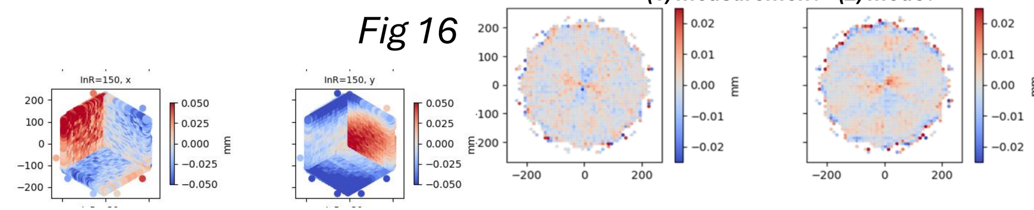


Fig 16

4. Performance 3: Auto Gude

Focus position of AG
- The AG focus position was compared with the fibers' focus position.
  - Construct PSF by shifting the fiber from the target in Gaussian distribution.
  - Fibers' focus position (where RMS of constructed PSF is minimum) is the same as the average focus position of the AG cameras for the blue arm. The red, NIR arm are shifted by ~50 um and 100 um, respectively (Fig 19).
  - AG1 focus position was shifted by 300 um in 2024, when its shutter was removed.
    - Compensation was done by changing the thickness of the glass window (Fig 20).
  - After modifying AG1 glass window in May 2025, the focus position among the AG cameras became the same within up to a few tens of um (Fig 21).
    - Each camera show a sinusoidal variation w.r.t. InR (similar to HSC) (Fig 22).


Fig18

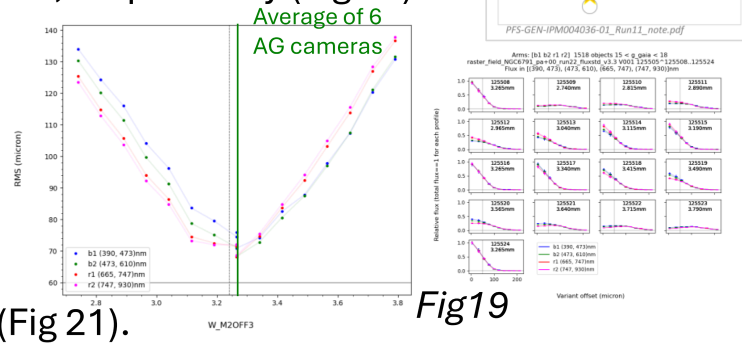


Fig19

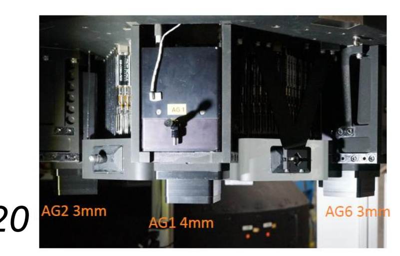


Fig 20

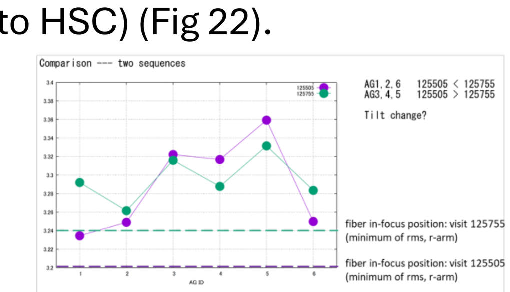


Fig 21

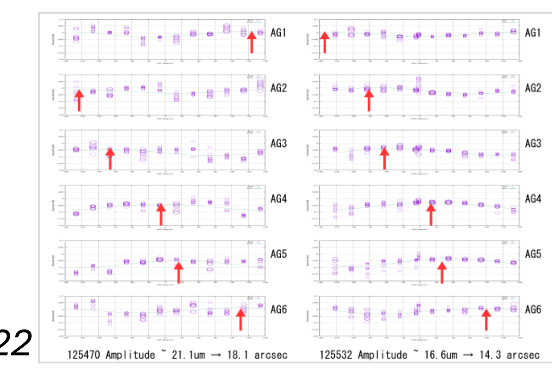


Fig 22

Guide performance
- "Commanded" error to the telescope is order of ~0".1 in each axis (i.e. Az and El).
  - The fields with few stars show larger error.
    - Adding the HSC catalogue stars, which is deeper than Gaia catalogue, is under development and test.
  - Measurement of each camera show larger variation (up to ~0".5) in lateral, and shift in focus by several tens of um, which suggests instability of the camera position (Fig 23).

Instability of the camera position
- It is thought that a gap was created between the camera body (Aluminum) and its holder (Invar) due to temperature difference between Taiwan and the summit.
  - The current support doesn't hold the body in the radial direction.
  - Adding the camera support is planned.

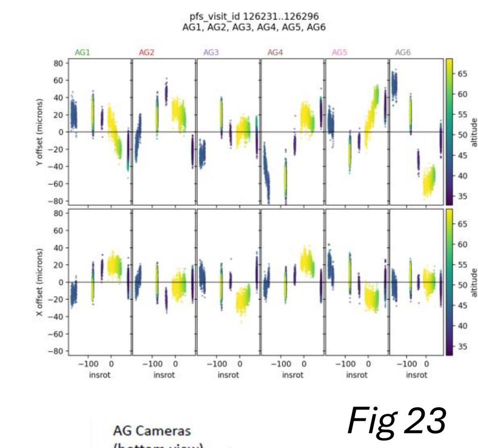
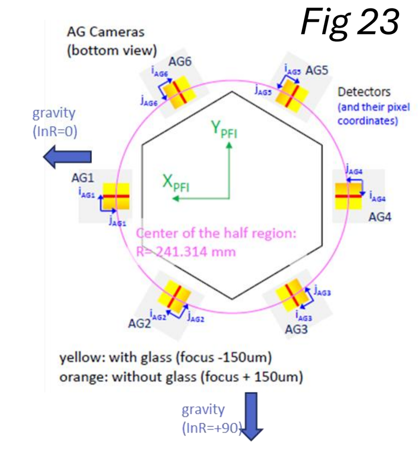


Fig 23



5. Remaining Issues

To stabilize and optimize the PFS instrument performance, the below items remain to be done.
- Improve the fiber configuration accuracy.
- Monitor convergence rate.
- Instrument upgrade (in the S26A semester)
  - Replacement of the H4RG detector in the SM2 NIR camera, because of its persistence (very long decay time, Figs 24&25)
    - Note: all the detectors have persistence (and in very short time scale, impact of SM1/SM4 is lager, Fig 26)
    - DRP team is developing a method to correct persistence.
  - Upgrade of the AG camera support (Fig 27).
- Developing the gel cleaning machine is also being developed for the Cable B (Fig 28)

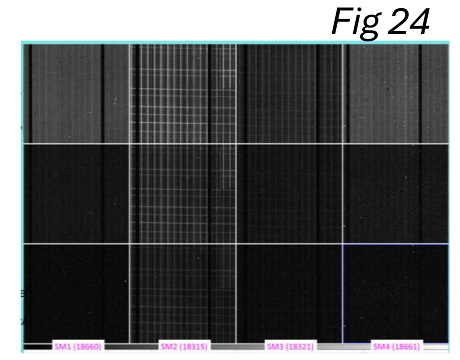


Fig 24

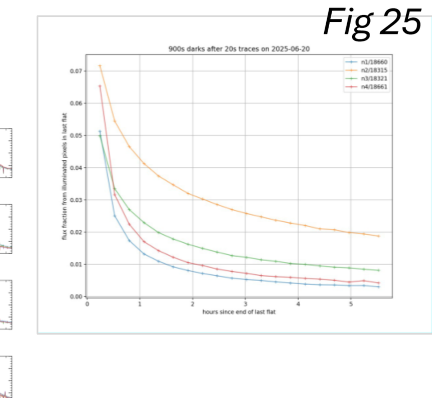


Fig 25

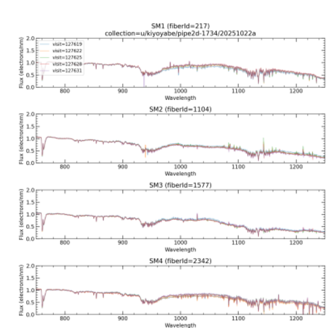


Fig 26

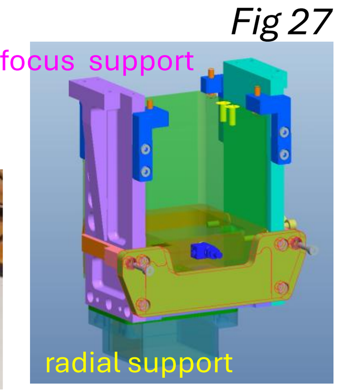


Fig 27

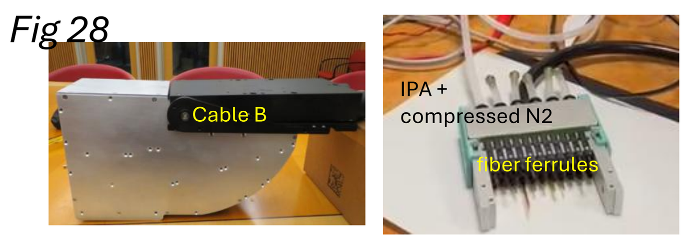


Fig 28