Four-year operation of IMC instrumented baffle in Virgo

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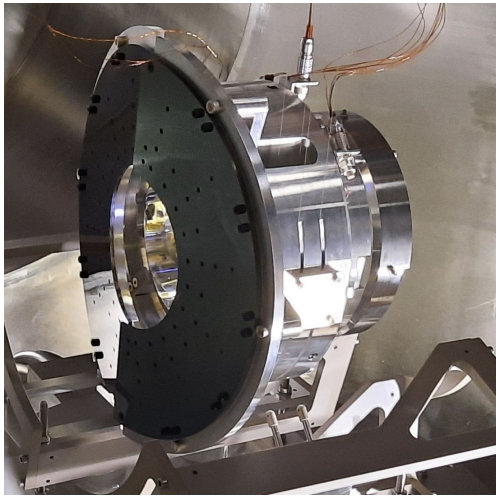
Mitigating and controlling stray light

- Stray light is laser light scattered or reflected by optical defects, deviating from its intended path and **recombining with the main beam with delays and phase differences**.

- **Important contribution to the technical noise budget:** stray light noise degrades the laser's frequency stability and reduces the instrument's sensitivity.



- Baffles are low-reflective low-reflective **devices developed to mitigate stray light.**

- Placed in optical cavities of Virgo **since O1.**

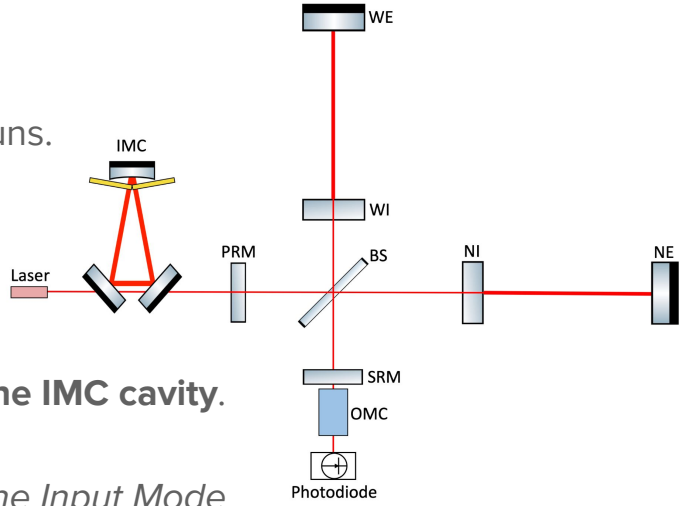
- **Baffle instrumented with photodiodes** installed in the input mode cleaner (IMC) cavity in April 2021 (**post-O3**) as a demonstrator of the technology.

An instrumented baffle in the IMC of AdV+

- The IMC baffle was installed in April 2021 as a **demonstrator of the instrumented baffle technology in view of the installation of instrumented baffles in the main arms for O5.**

- It has been **operating continuously** for more than 4 years: during O4 commissioning and during O4b and O4c observing runs.

- The aim of the following analysis is to demonstrate that:
  - the IMC baffle is **operating stably**,
  - the IMC baffle is **sensitive to changes in the cavity,**
  - the IMC baffle is **not compromising the performance of the IMC cavity**.



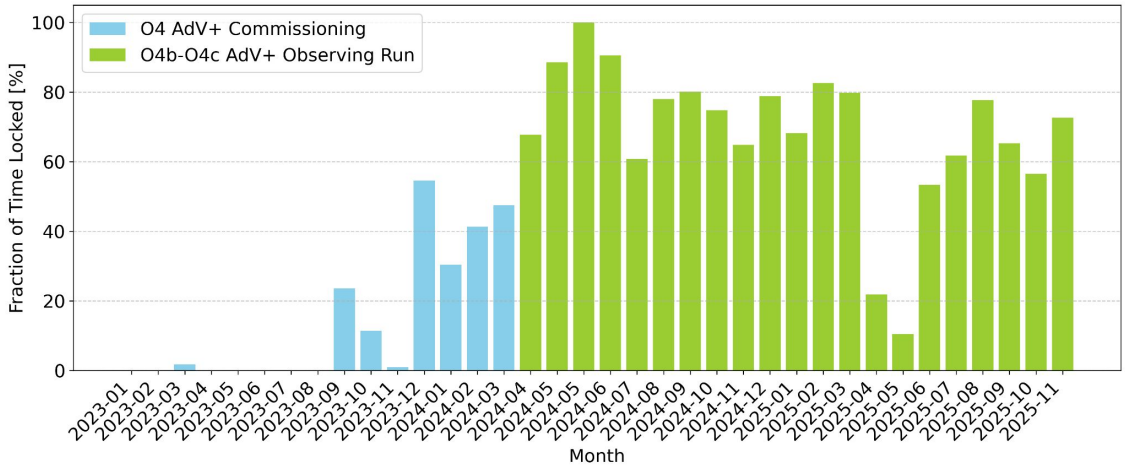
- Publication (to be submitted soon): *The Instrumented Baffle at the Input Mode Cleaner of Advanced Virgo+: Four years of successful operation as a monitor of stray light*

See previous publications (Ballester+22 [2111.09312], Romero-Rodríguez+20 [2008.13740], Andres-Carcasona+23 [2210.16313]

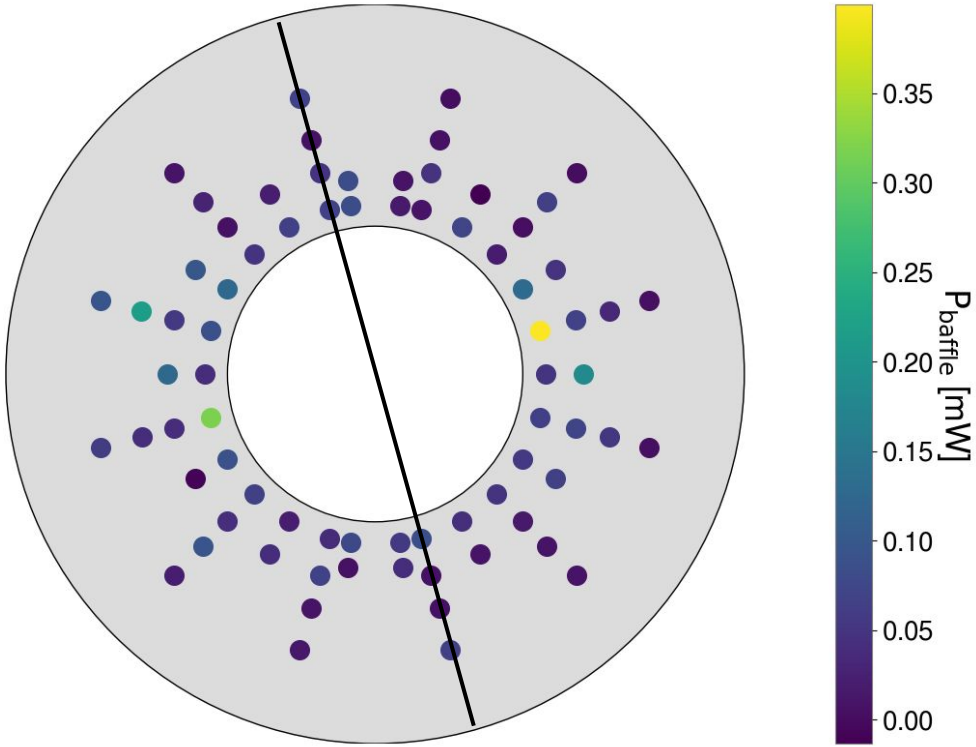
Status of AdV+

Commissioning activities are significantly affecting the fraction of laser power lost as stray light and measured by the IMC baffle. The significance of a long term analysis should therefore be interpreted in close connexion with simultaneous commissioning activities.

In particular, the change in laser input power and the method for the alignment of the laser beam in the IMC cavity are expected to have a direct impact.

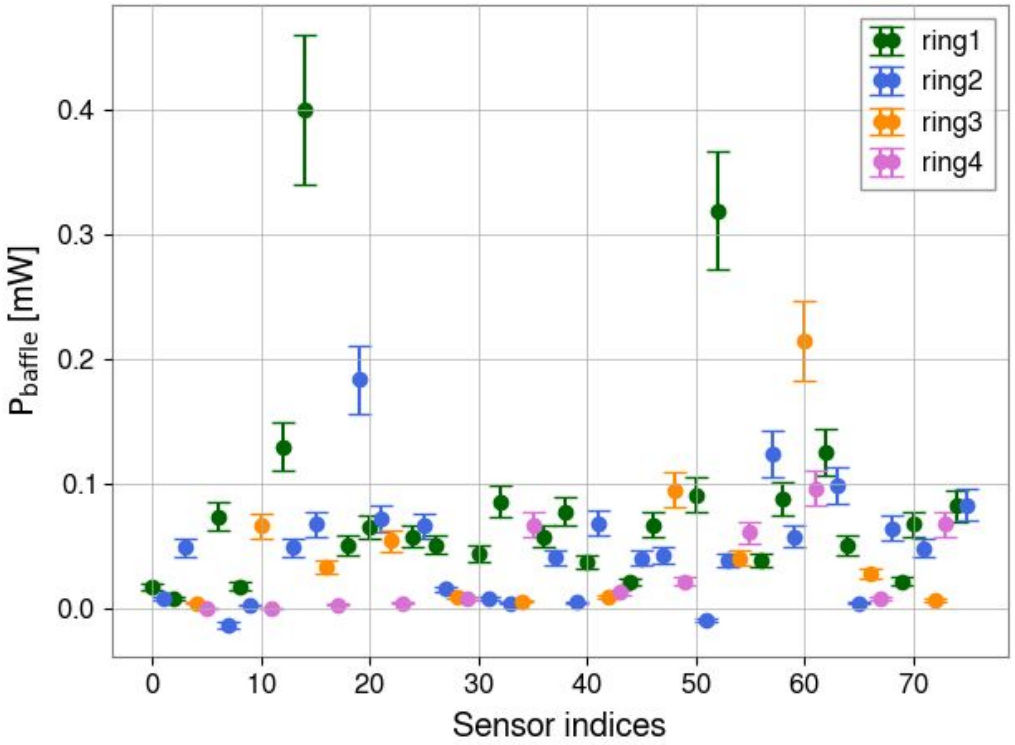


Spatial distribution of scattered light



- **Total power** measured by the baffle adds up to **a few mW**.
- The individual **variance is well below the µW level**.
- Inhomogeneous stray light distribution:
  - Innermost rings / **low angles** most illuminated,
  - A few sensors account for the majority of the measured power,
  - Axis of symmetry tilted by 9 degrees.
- **Results expected from simulations.**

Spatial distribution of scattered light



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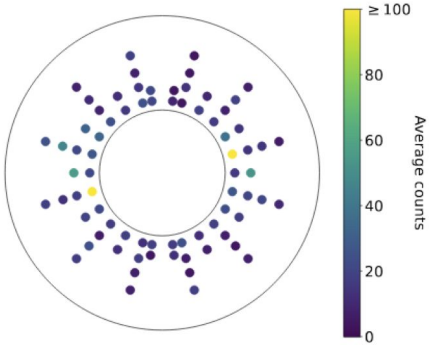
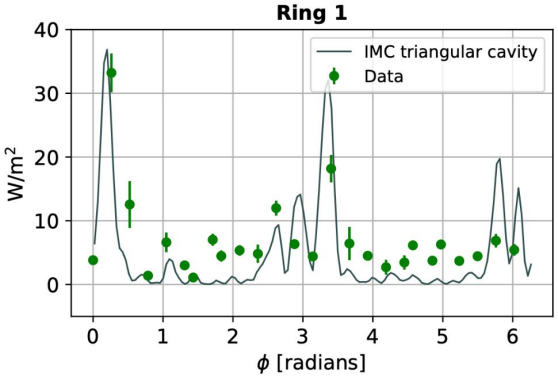
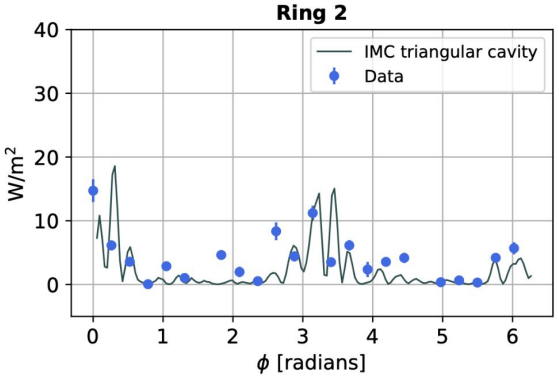
Spatial distribution of scattered light

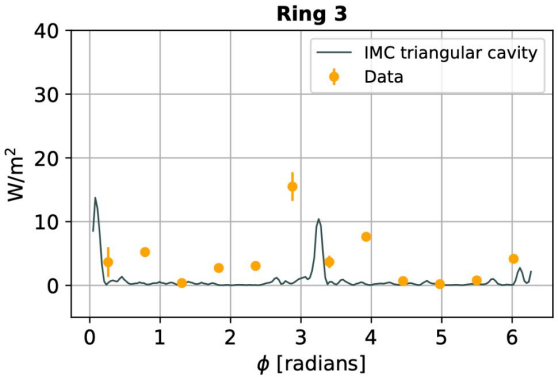
- Plot adapted from Ballester+22 to compare data from May 2024 and simulations with an input power of 18W.
- Results agree with simulations.

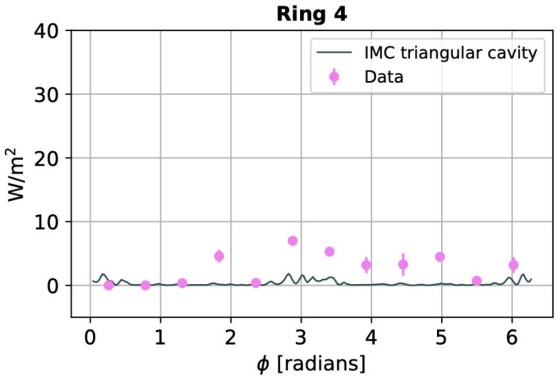


From Ballester+22







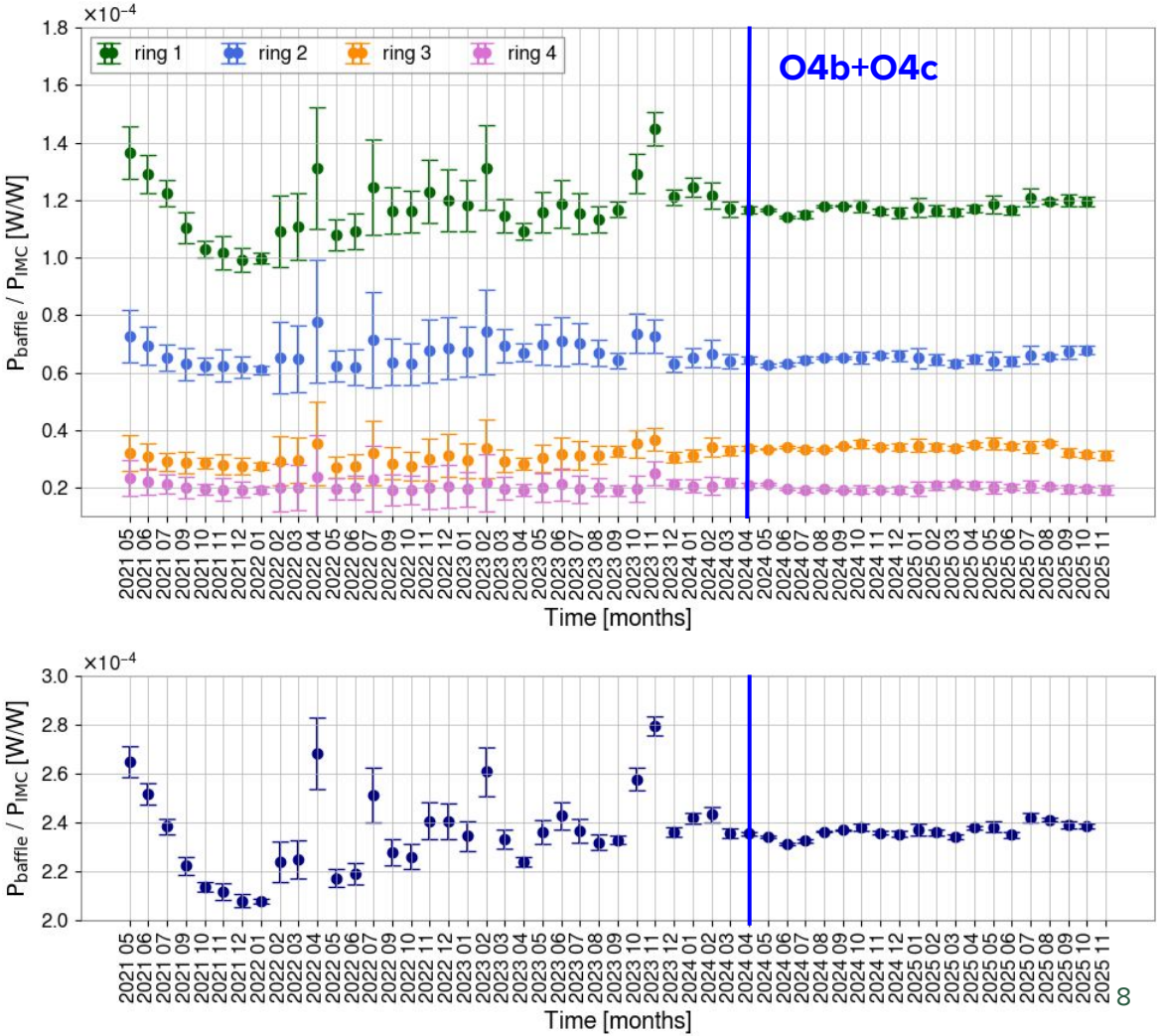


Temporal evolution

- Results are normalised by P_{IMC}: **0.2-0.3 % of intra-cavity power is measured as stray light**. Ratio is very stable.

- Low angles are consistently more illuminated: **ring 1 sees 50% of the power measured by the baffle**.

- Variance is noticeably lower starting in early 2024 when approaching O4: **baffle sensitive enough to capture shift between commissioning and science run.**



Connection to the interferometer

We know of the importance of **taking into account the status of the interferometer (ITF) to assess the stability of the baffle**. Normalising by the input intra-cavity power was crucial. However we still see that **the response of the IMC baffle differs during commissioning and the science run** and we are interested in understanding what in the ITF can be responsible for those variations.

We assess the role of the instrumented baffle as an active monitoring device by studying the relationship between baffle data with:

- the stability of the injection (INJ) system,
- the alignment strategy,
- the environmental monitoring,
- the presence of strong transient signals.

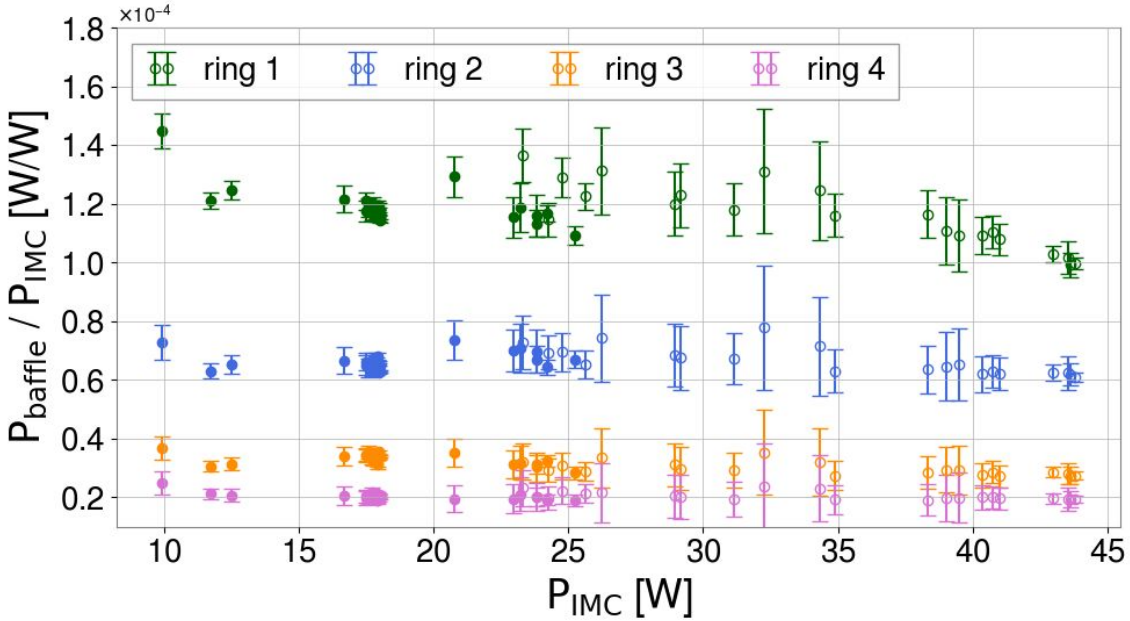
Relying on stray light patterns to understand misalignment and mirror aberrations/deformations can be done by close comparison with simulations.

Connection to the ITF: INJ system stability

- Understanding the INJ system stability is crucial to study stray light.

- **Does P_{baffle}/P_{IMC} vary with P_{IMC}?**
  Overall, no.
  A linear decrease in stray light with PIMC is observed in the innermost ring for PIMC>35. A tentative explanation is **mirror-related thermal effects**, as IMC mirrors lack a thermal compensation system.

- Study of correlation with other INJ auxiliary channels was inconclusive.



Full markers indicate O4b and O4c months, empty markers the remaining months. Error bars show the 3σ confidence level over each month (between May 2021 and November 2025, except August 2021 and 2022).

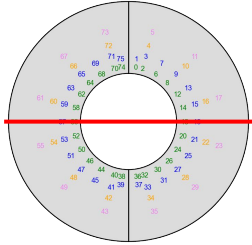
Connection to the ITF: Alignment strategy

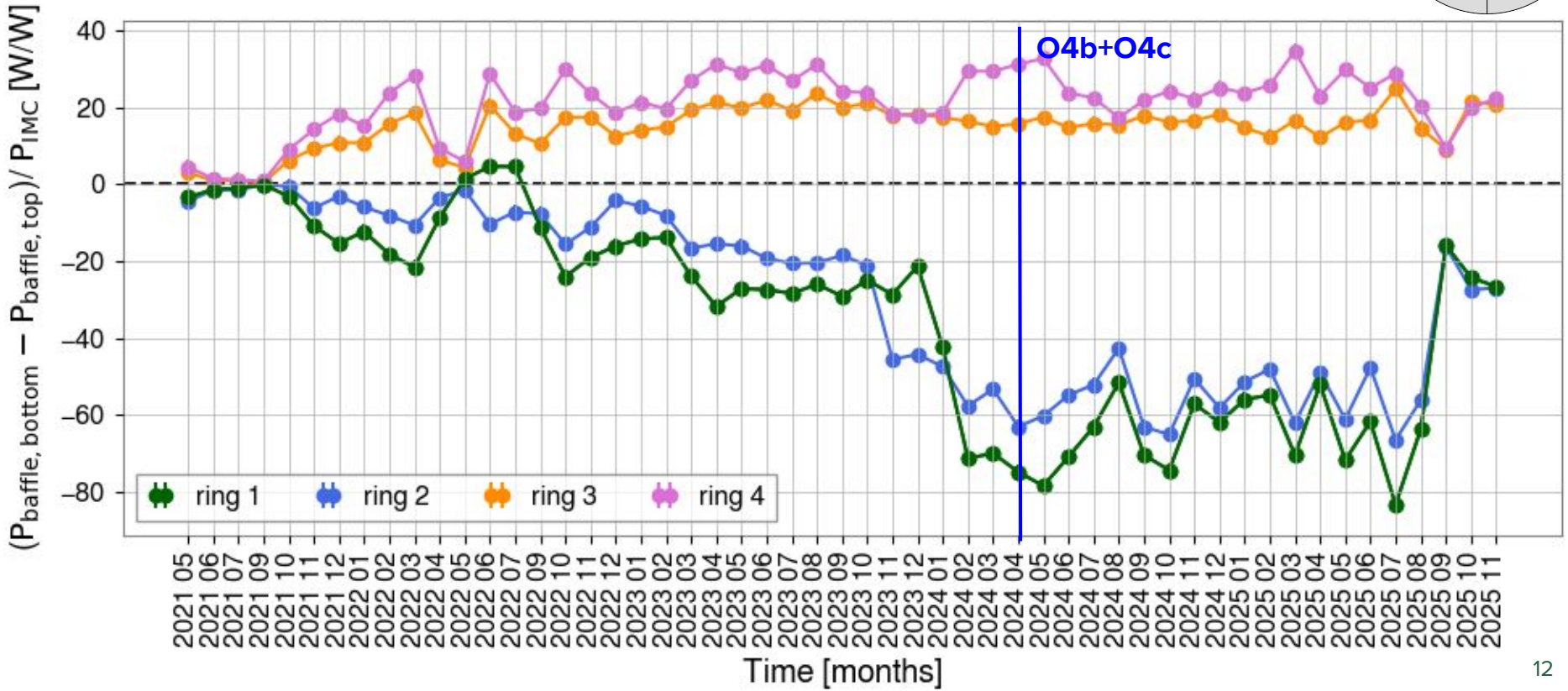
- **Axial asymmetry of the stray light distribution was identified.**
- Originates from the geometry of the cavity and mirror maps, as shown by simulations.
- We study the **evolution of the vertical (bottom-top) and horizontal (left-right) symmetry** and compare it with the **IMC beam alignment channels**.

Our conclusions are:

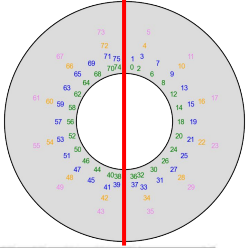
- **Rings 1 and 2** only are sensitive to changes in symmetry.
- There was an **increase in asymmetry** in early 2024, approaching the start of O4b.
- There is **good agreement with the Virgo alignment channels.**

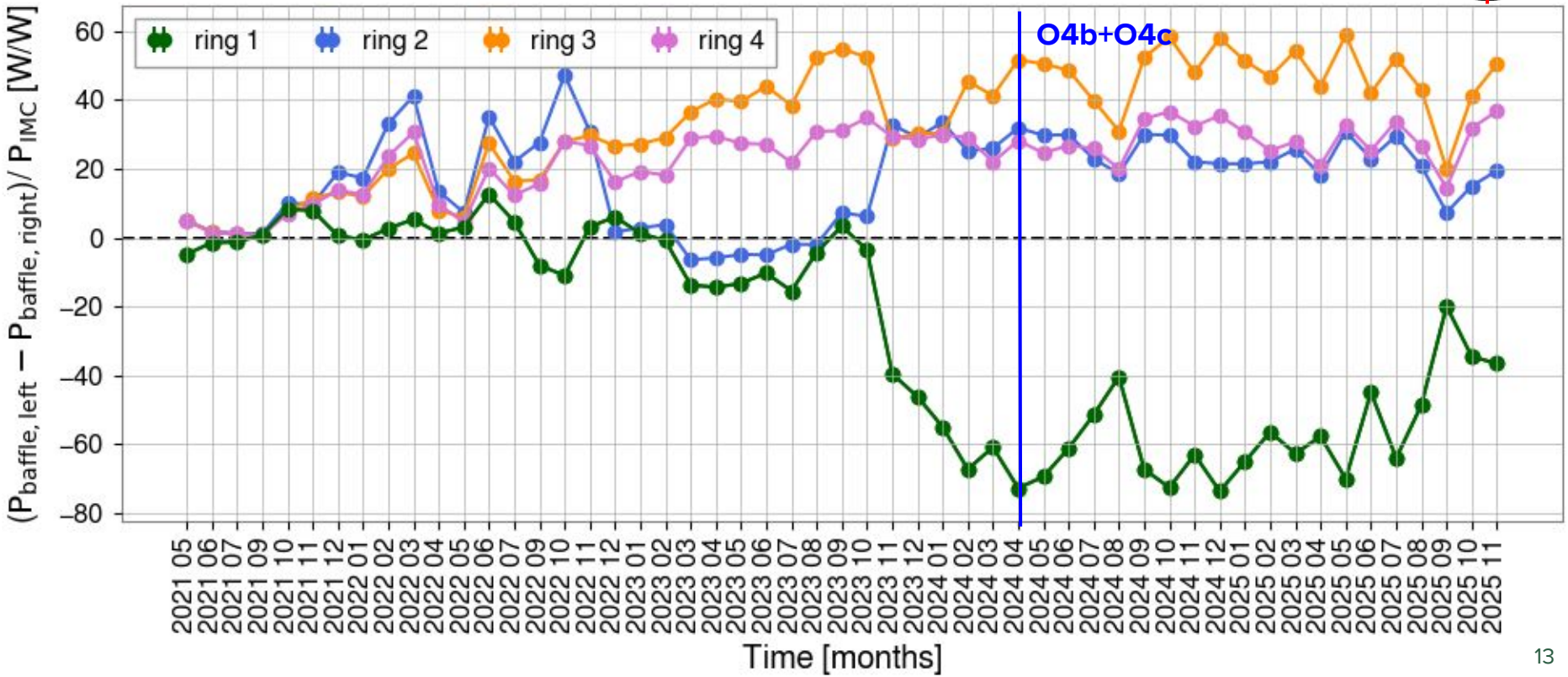
Evolution of the vertical symmetry



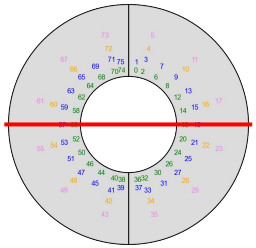


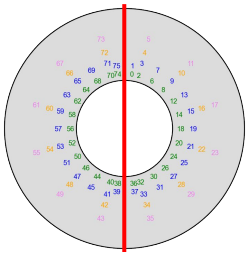
Evolution of the horizontal symmetry

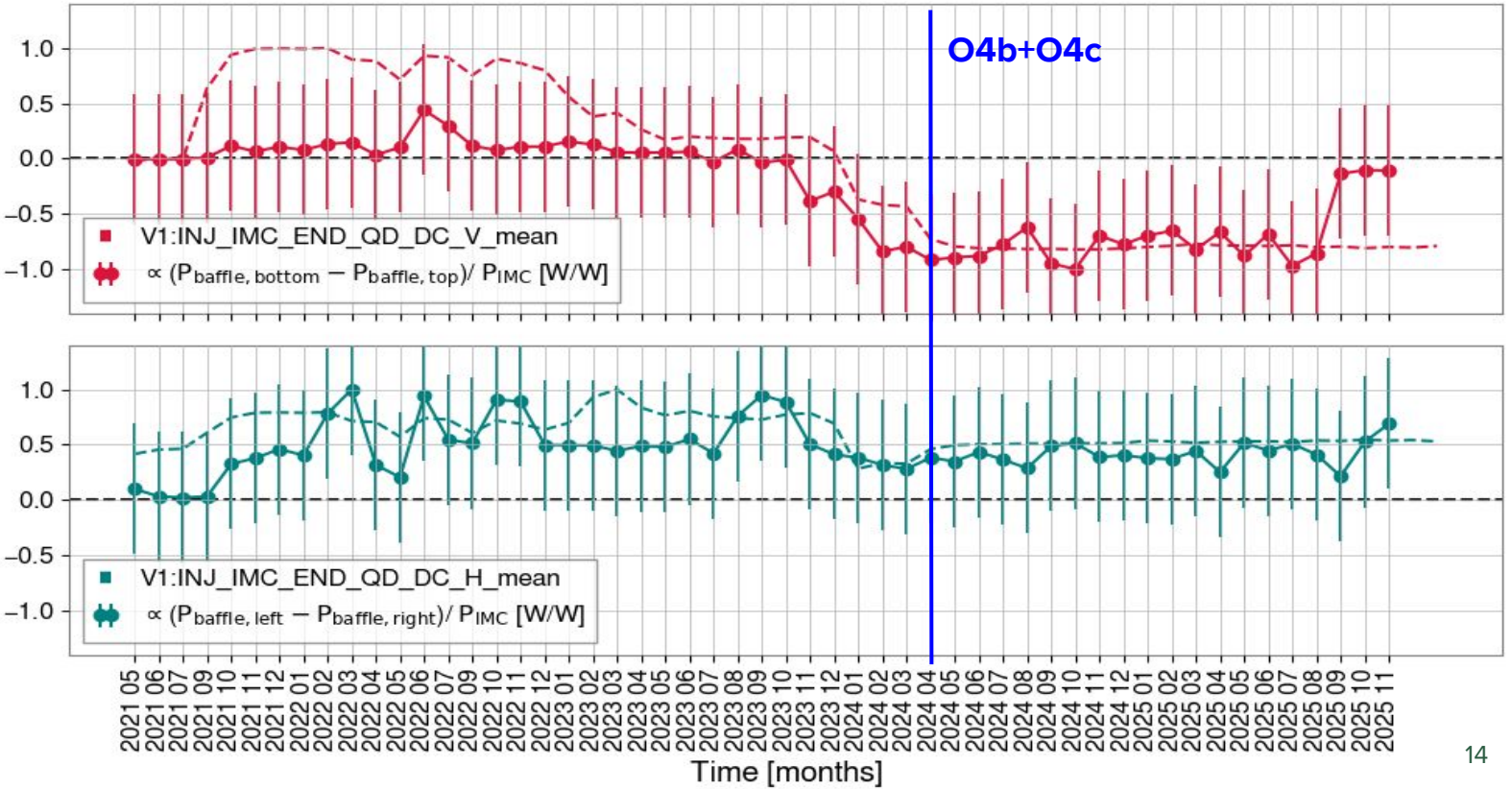




Comparison with the IMC beam alignment channels







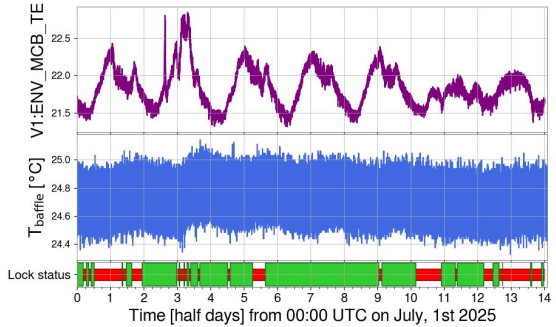
Connection to the ITF: Environmental monitoring

Seismic activity

- **We expect the scattered light to be more important during periods of high seismic noise.**
- Use channel V1:ENV_MCB_SEIS_W_rms
- Sporadic correlation between increases in scattered light but not consistent enough to draw strong conclusions but **it suggest that environmental fluctuations indeed play a role in the increase of stray light.**

Temperature

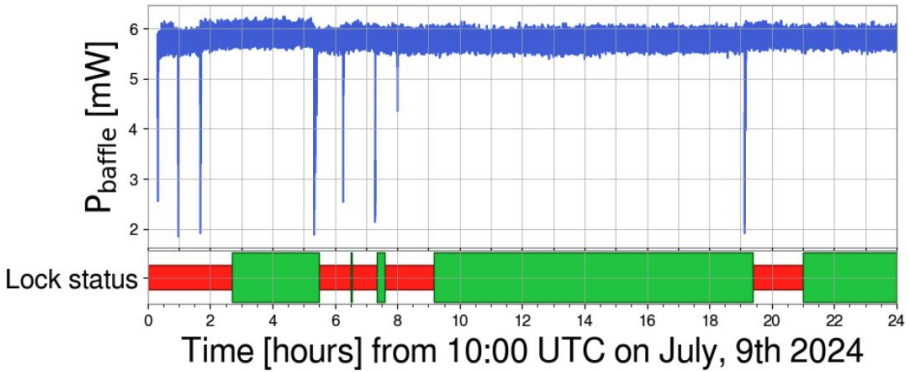
- **Study of the correlation between ADC counts and temperature**.
- Some sensors exhibit 24-hour and 12-hour periodicity.
- Inconclusive owing to the very limited number of sensors and months during which this behaviour was observed.

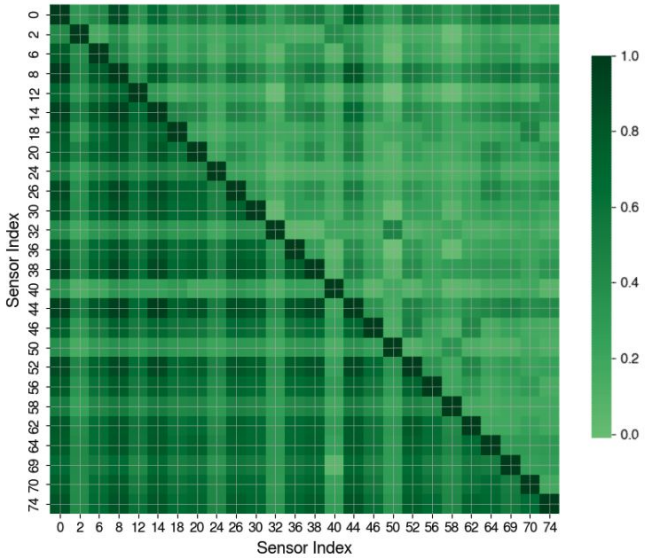


Connection to the ITF: transient signals

- Stray light distribution is highly dependent on the **presence of glitches or other transient signals that result in a sudden increase of light in the cavity**.

- Sensors have a **coherent response** to transients happening during **unlocks and lock acquisition states.**





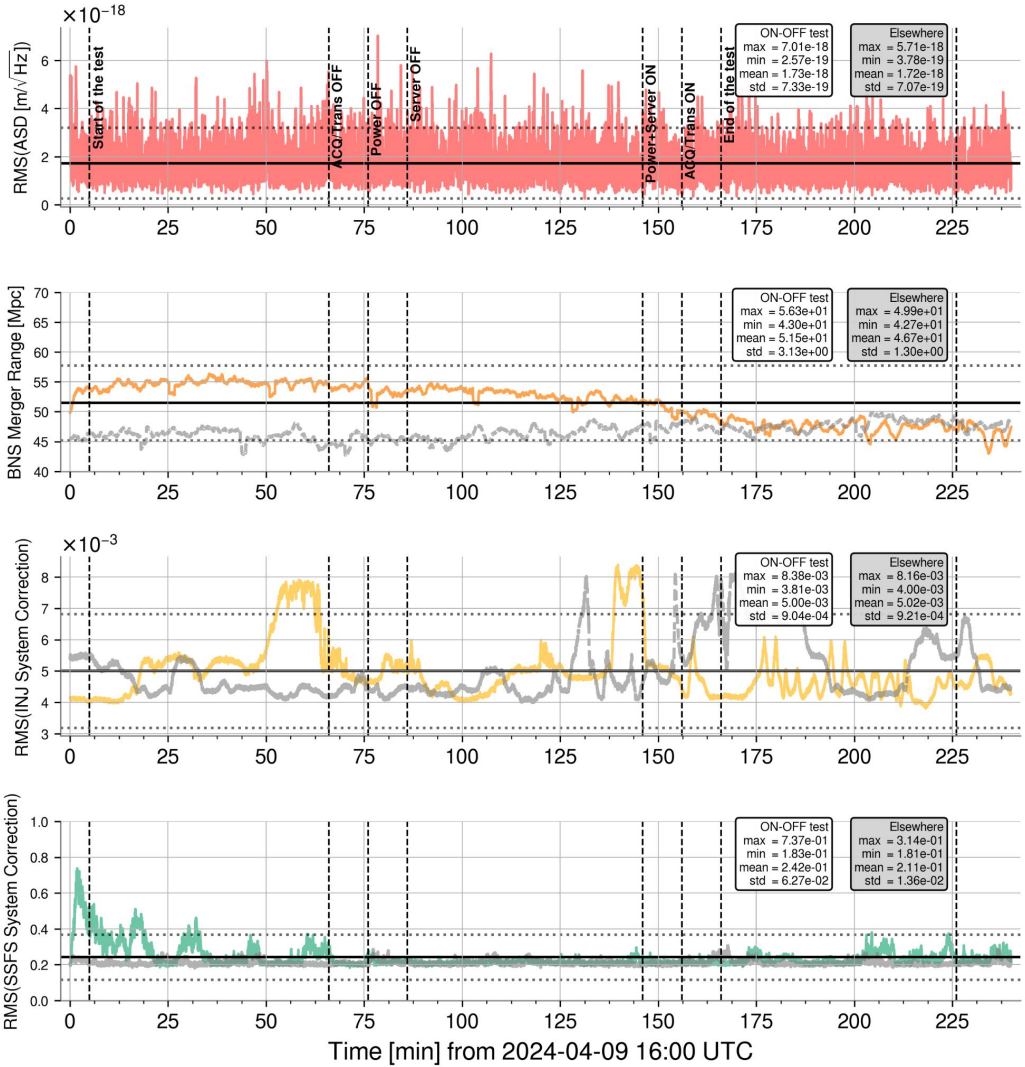
Correlation matrix for baffle sensors in ring 1. The lower triangle shows correlations for raw data, while the upper triangle shows correlations for data filtered with a 1σ cut to remove transients.

Noise level assessment

- Sequential switch-off and switch-on of the baffle devices.

- Study behaviour of channels and spectrograms to check for:
  - Large variations in the amplitude spectral density (ASD),
  - Decrease in BNS merger range,
  - Abnormal correction signals related to the laser INJ system and laser frequency stabilisation (SSFS),
  - Magnetic interference in the IMC building.

- No correlated behaviour was found.



Conclusions

Since its installation in 2021, the baffle has displayed **good stability** throughout the months of commissioning. The results match what was expected from simulations.

Stability and performance are improved during the science run, validating prior observations and allowing us to look at the data more in-depth.

Through the study of the correlation between the scattered light seen by the baffle and channels indicative of the laser status, we are able to **follow the alignment of the laser beam in the IMC and the presence of transient signals in the laser with the instrumented baffle data**. **The instrumented baffle complies with its role as a monitoring device around the IMC end-mirror.**

Noise level assessments were conducted, including as part of noise hunting activities in March 2024 and previously in October 2022. The baffle was shown to cause **no increase in the noise level**.