Stray Light issues and control in Advanced Virgo Plus

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GRAvitational - wave Science&technology Symposium (GRASS)
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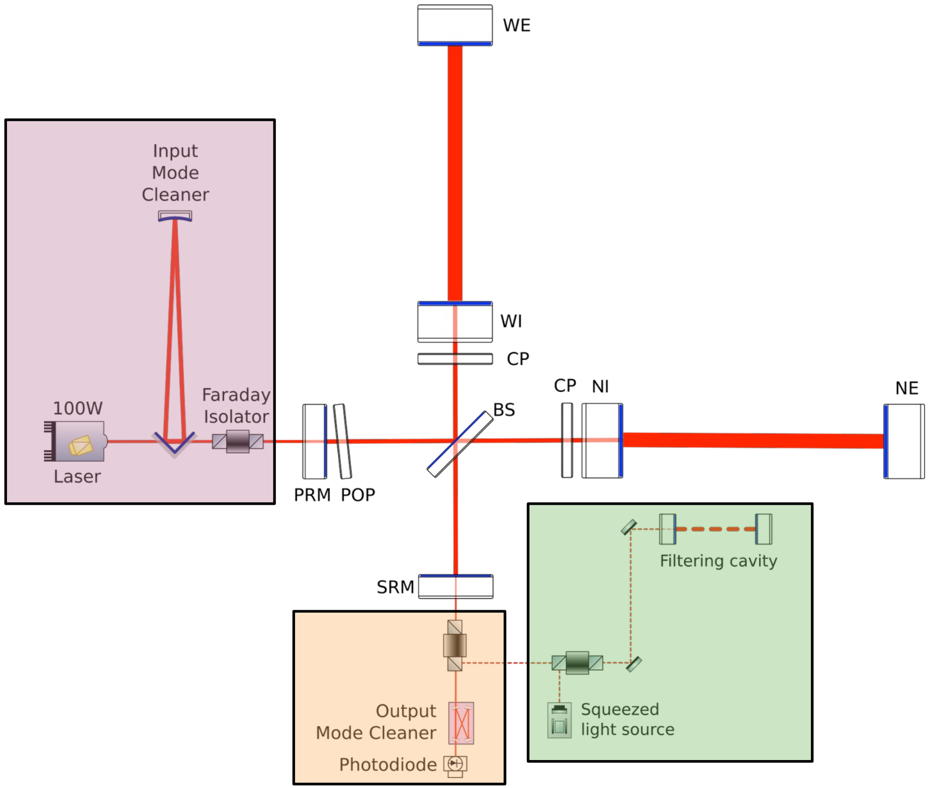
Overview – Stray Light in AdV+

Stray light limited the sensitivity of Advanced Virgo and will limit Advanced Virgo Plus

Actions to study/reduce stray light in AdV+:

- Ghost beam tracing and dumping everywhere:
  - **Injection** (INJ) system
  - **Detection** (DET) system
  - **Frequency Dependent Squeezing** (FDS) system
- Back-scatter measurement with an interferometric scatter meter (at LAPP)
- Development of feedback loop to reduce stray light:
  - Example in the squeezing system



Stray light from suspended bench in O3

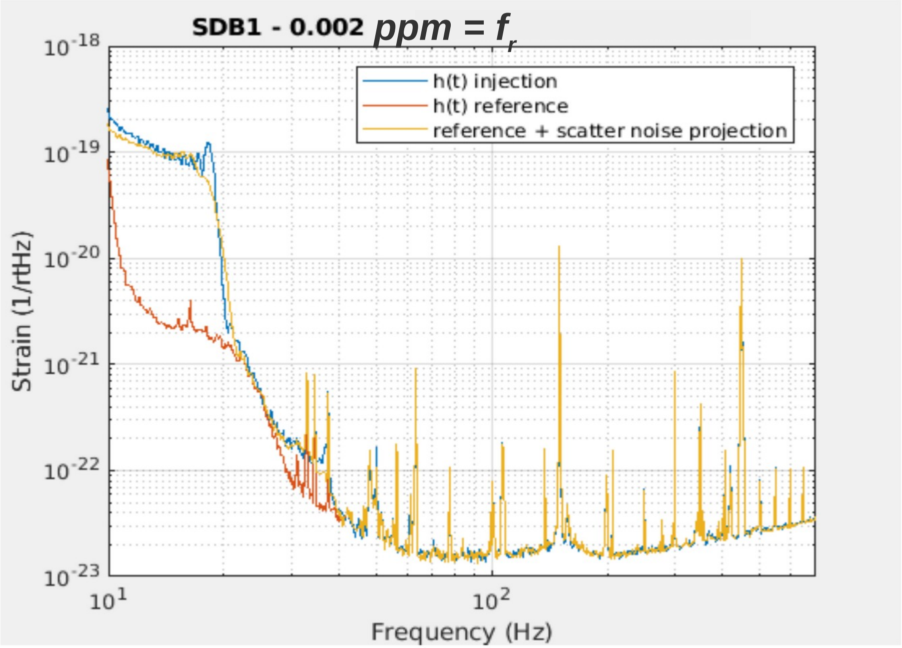
Fraction of light power coupled back with the main mode of the ITF

Fourier transform

$$\tilde{h}(f) = T(f)\sqrt{\frac{f_r P_{out}}{P_{in}}}\,\mathscr{F}\left[\cos\left(\phi_r(t)\right)\right]$$

Transfer function: linear response of the ITF to noise

Phase variation of the re-coupled field



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Stray light contributions

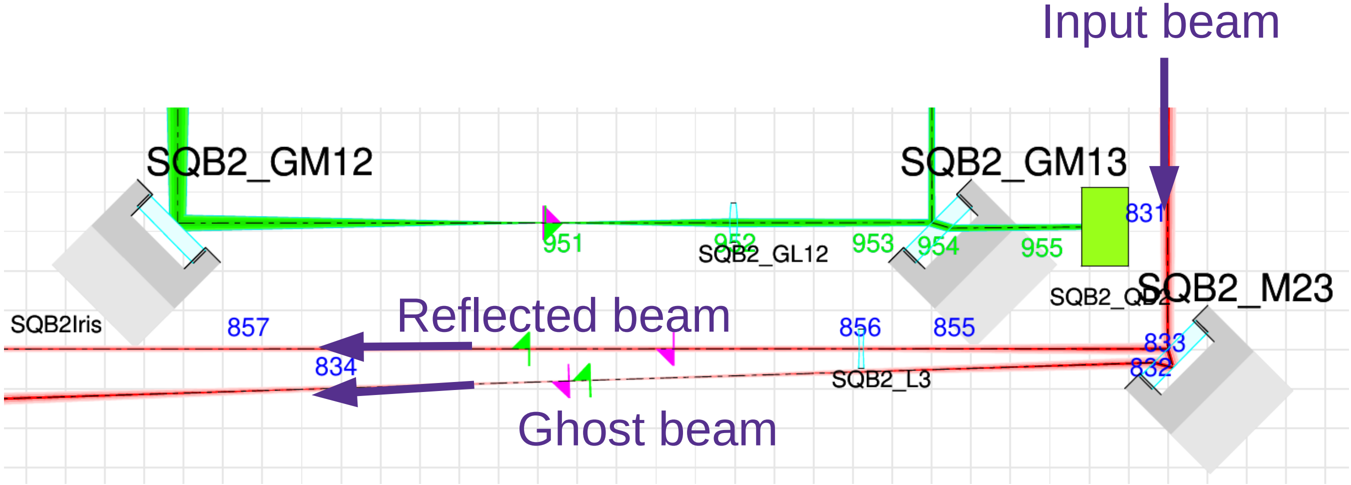
Fraction of light back-scattered by the main optics (mirrors...)

Fraction of back-reflected re-coupled light (lenses, photodiodes...)

Fraction of scattered light by atoms or molecules, i.e. crystals (TGG)

$$f_r = f_{sc} + f_{sp} + f_{Rayleigh} + \boxed{f_{extra}}$$

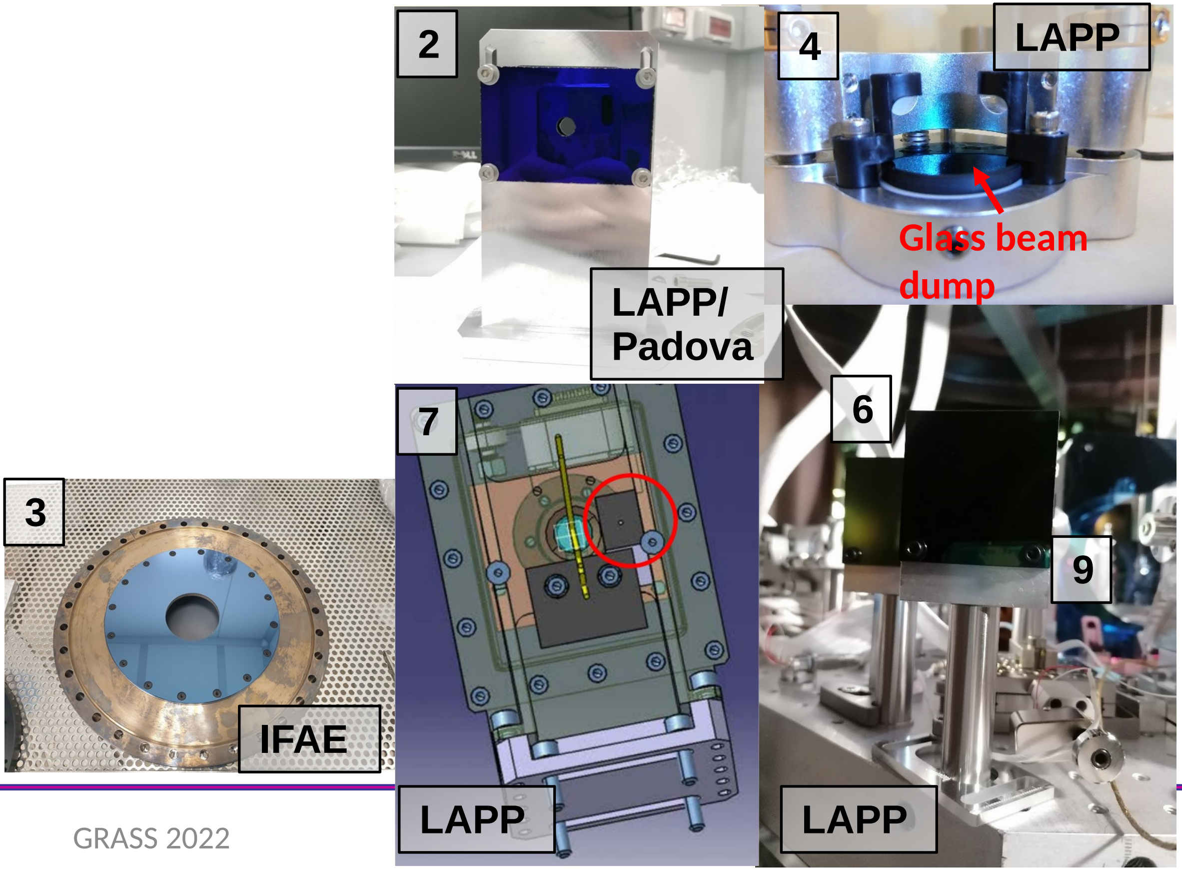
Ghost beams are unwanted secondary beams generated by not perfect HR and AR coating of optical components, like mirrors. They propagate on the benches hitting mounts, optics, vacuum chambers etc causing ***extra** scattered light* !



Ghost beams mitigation

Some of the *mitigation strategies* adopted for Advanced Virgo Plus:

1. Wedge optimization
2. Diaphragms installation
3. Baffle installation
4. Absorbing disks behind mirrors
5. Diaphragms on quadrants
6. Small beam dumps
7. Dumpers on photodiodes
8. Lens tilting
9. Absorbing screws



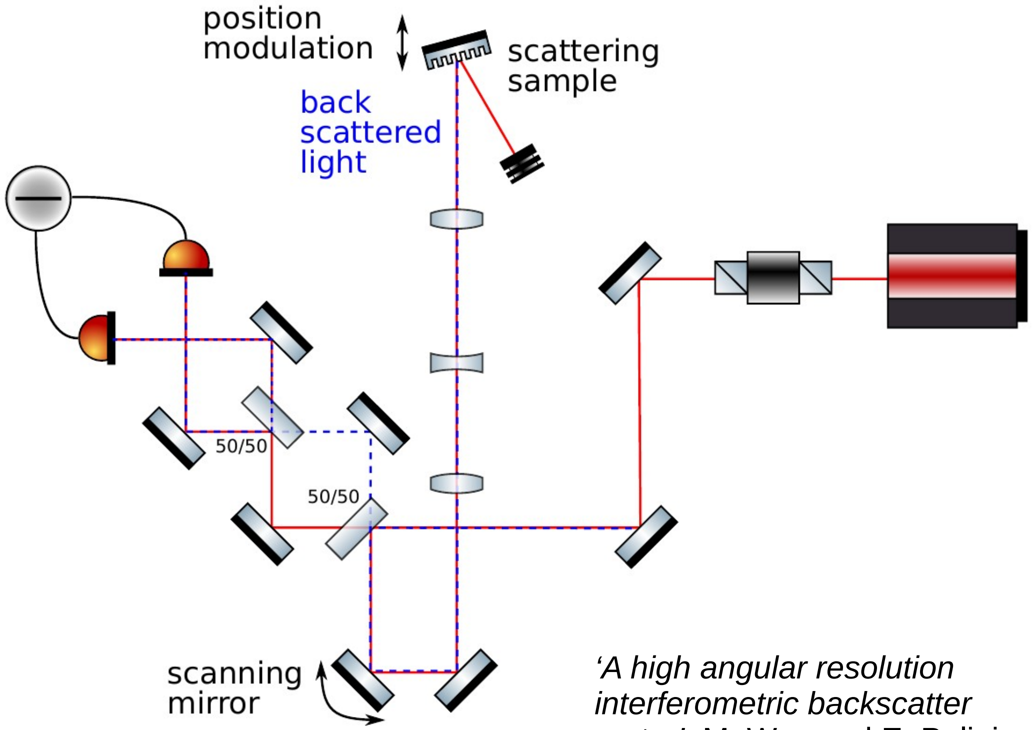
How to measure scattered light?

Measured back-scatter fraction with a balanced homodyne detector:

$$P_1(t) - P_2(t) = \frac{P_0}{\sqrt{2}}\sqrt{f_{sc}}\cos\left(2\pi\frac{\Delta L(t)}{\lambda}\right)$$

$$A(t) = \frac{P_1(t) - P_2(t)}{P_1(t) + P_2(t)} = \sqrt{2f_{sc}}\cos\left(2\pi\frac{\Delta L(t)}{\lambda}\right)$$

$$\mathrm{Var}(A(t)) = f_{sc}$$



'A high angular resolution interferometric backscatter meter', M. Was and E. Polini – Optics Letters (2022)

Back-scatter measurement

From the overlap integral between the EM field and the scattered light and assume it is *w(0)* the beam waist

$$\text{Overlap} = \left| \int_0^\infty 2\pi r E_{\text{beam}} E_{\text{sc}}^* \mathrm{d}r \right|^2$$

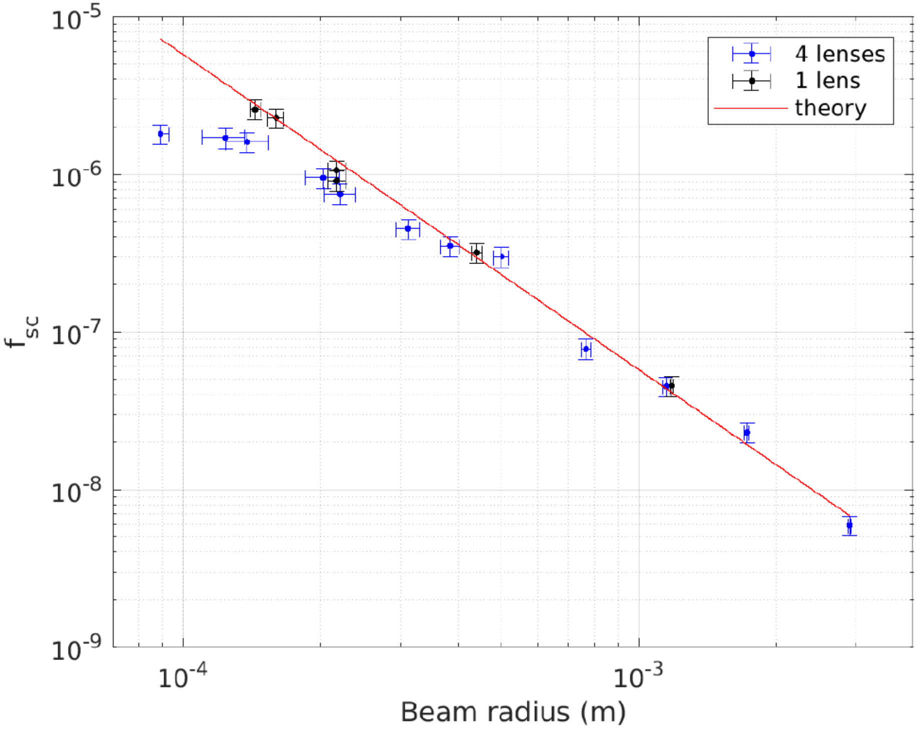
$$= \left| \int_0^\infty \frac{2r\mathrm{d}r}{wz} \exp\left[-\left(\frac{1}{w^2} + \frac{\pi i}{\lambda R} - \frac{\pi i}{\lambda z} \right) r^2 \right] \right|^2$$

$$\simeq \frac{1}{\frac{z^2}{w^2} + \frac{\pi^2}{\lambda^2}\frac{z_0^2 w^2}{z^2}} \simeq \frac{1}{\frac{\pi^2 w_0^2}{\lambda^2} + \frac{z_0^2}{w_0^2}} \simeq \frac{\lambda^2}{\pi^2 w(0)^2}$$

We derive the relation between back-scatter fraction f_{sc} and the beam radius at scattering surface:

$$f_{\text{sc}} = \text{Overlap} \times \pi \text{BRDF}(\theta) \cos\theta = \text{BRDF}(\theta) \frac{\lambda^2 \cos\theta}{\pi w(0)^2}$$

This formula has been demonstrated with this set-up.

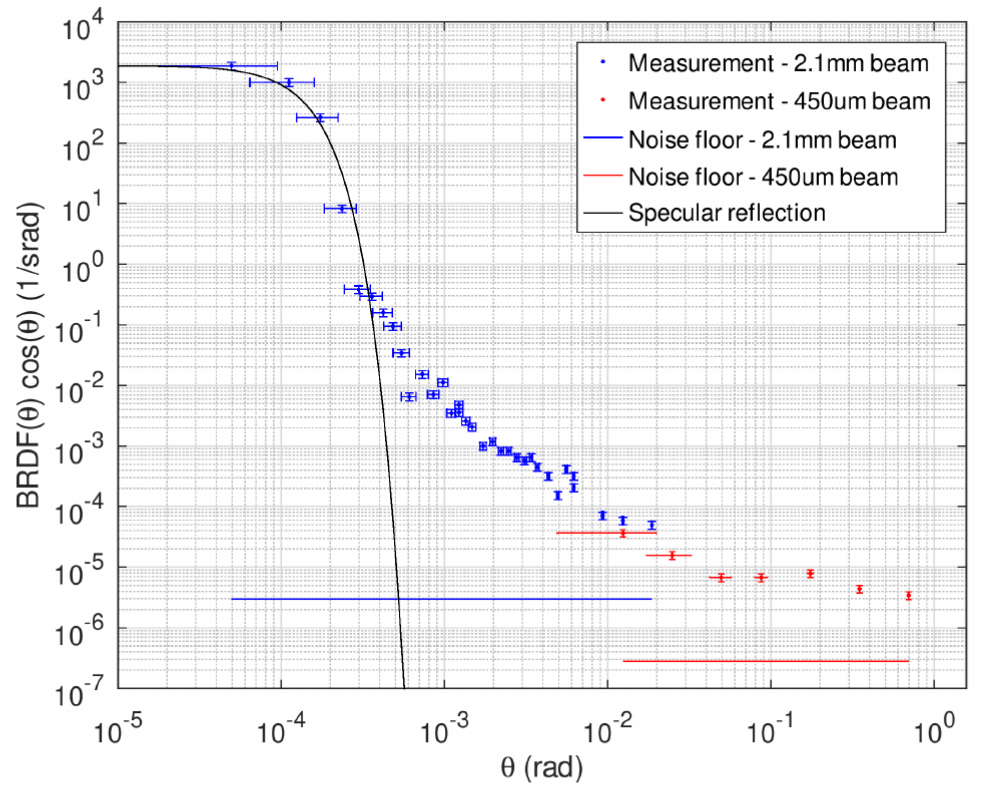


Back-scatter measurement

We measured the BRDF as a function of the incidence angle ϑ.

The measurement set-up achieved a 160 µrad angular resolution and measures back-scatter for incidence angles larger than 500 µrad.

Next steps:
To improve the set-up by increasing the telescope magnification by a factor 10 to reach a beam radius of 20 mm.
This will allow to measure angles larger than 50 µrad → GW core optics.



Stray light on FDS system

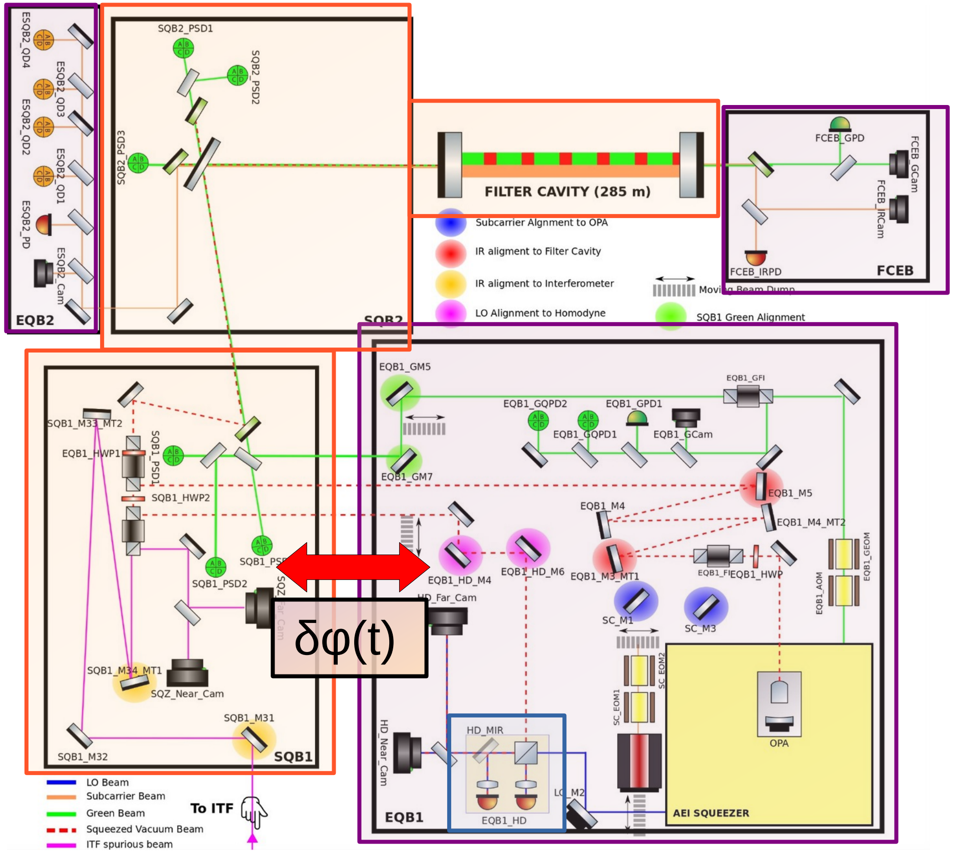
Suspended benches/cavity

$\delta\varphi(t)$

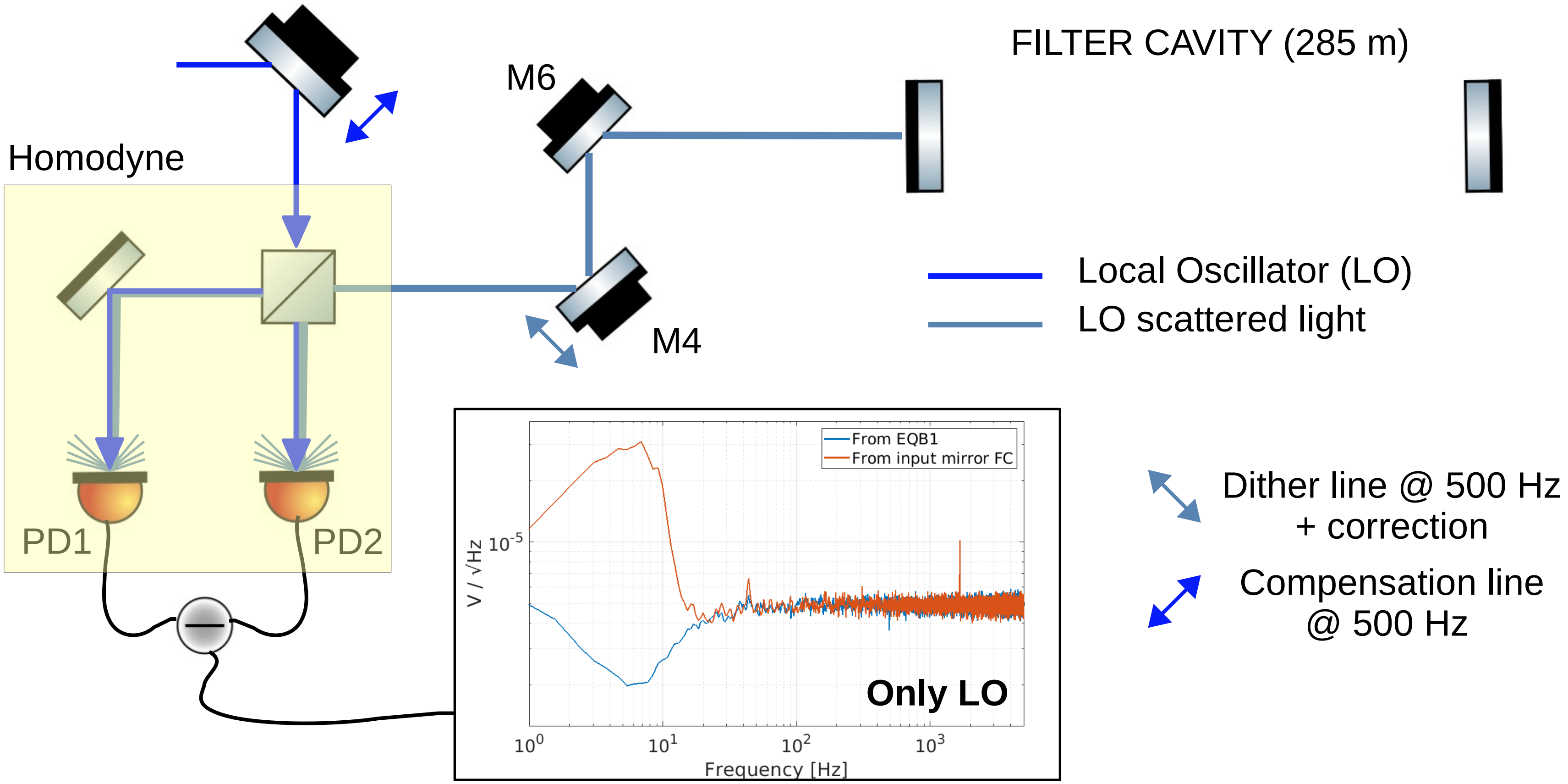
Ground-attached bench

Optical path modulation by residual motion of EQB1 and suspended optics causes a modulation of stray light optical path that induces additional noise in the

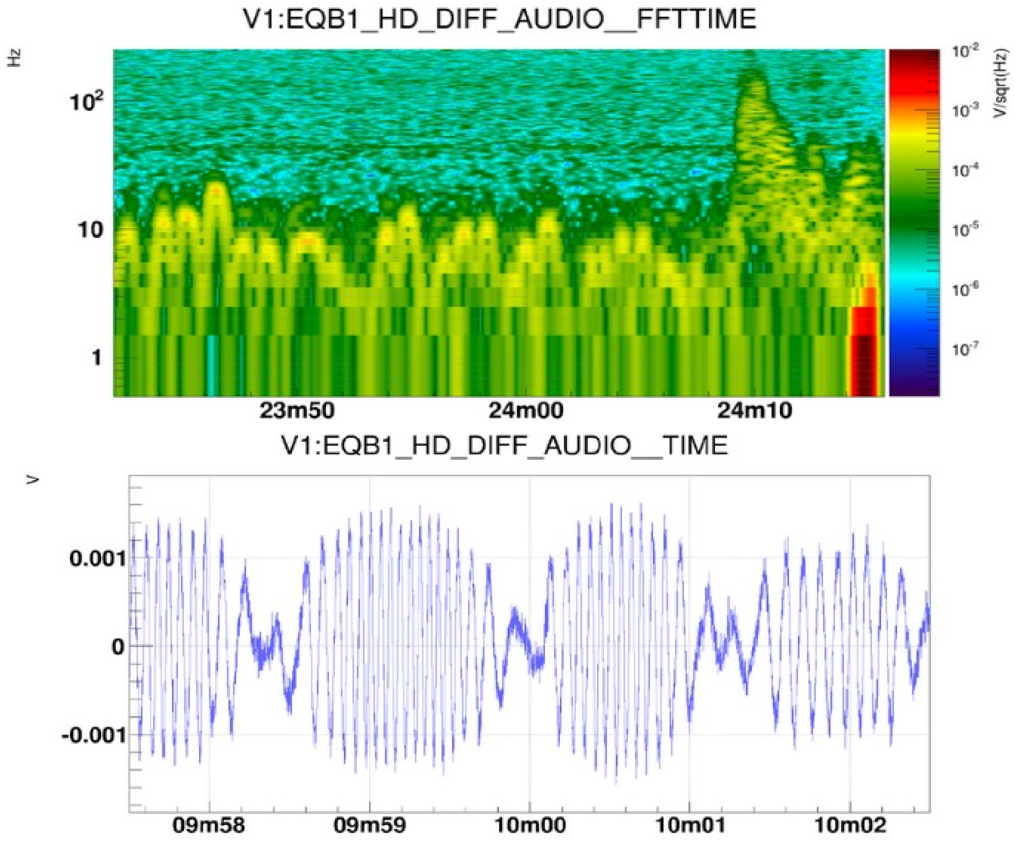
Homodyne detector



Stray light on FDS system



Stray light origin



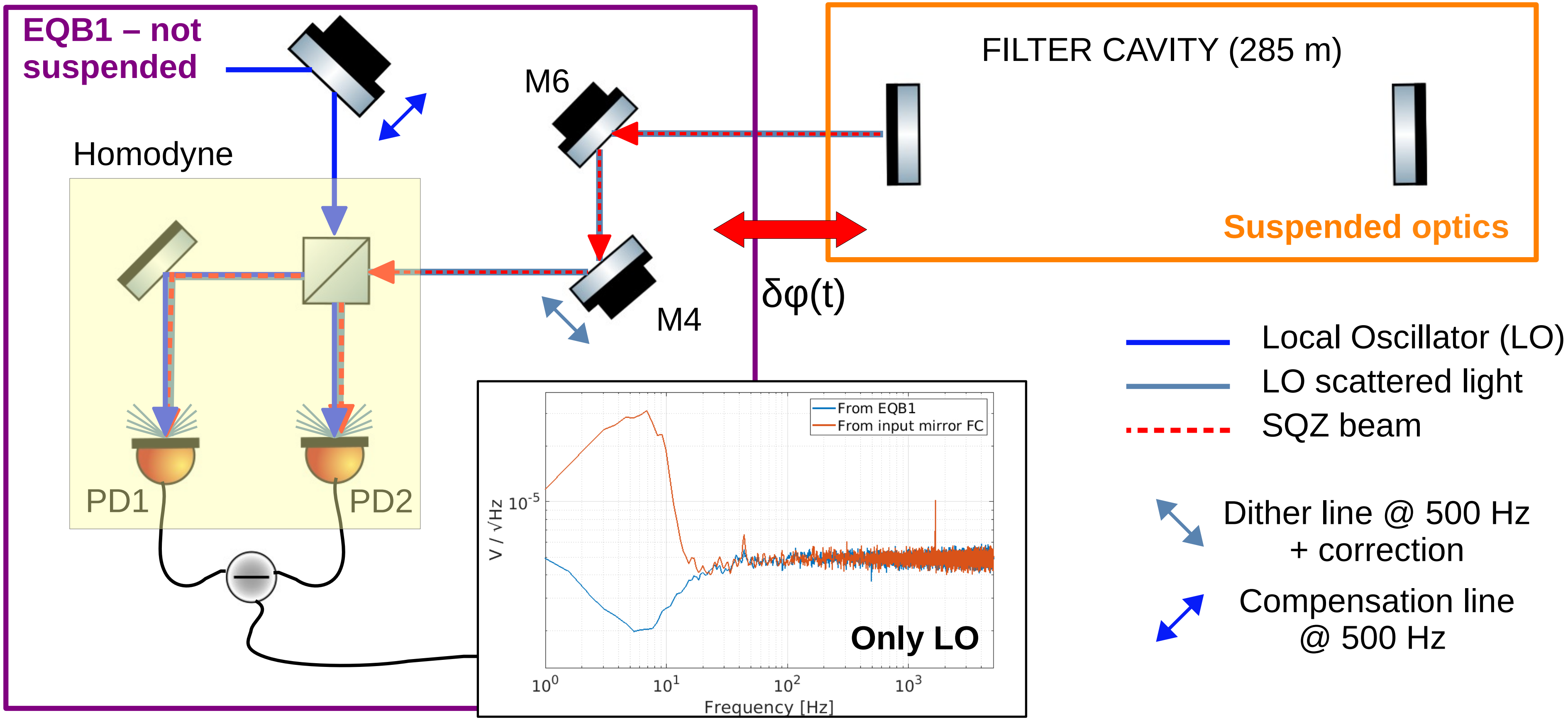
The spectrogram of the HD Difference audio channel shows typical stray light arches.

Observing this signal in time domain we can infer:

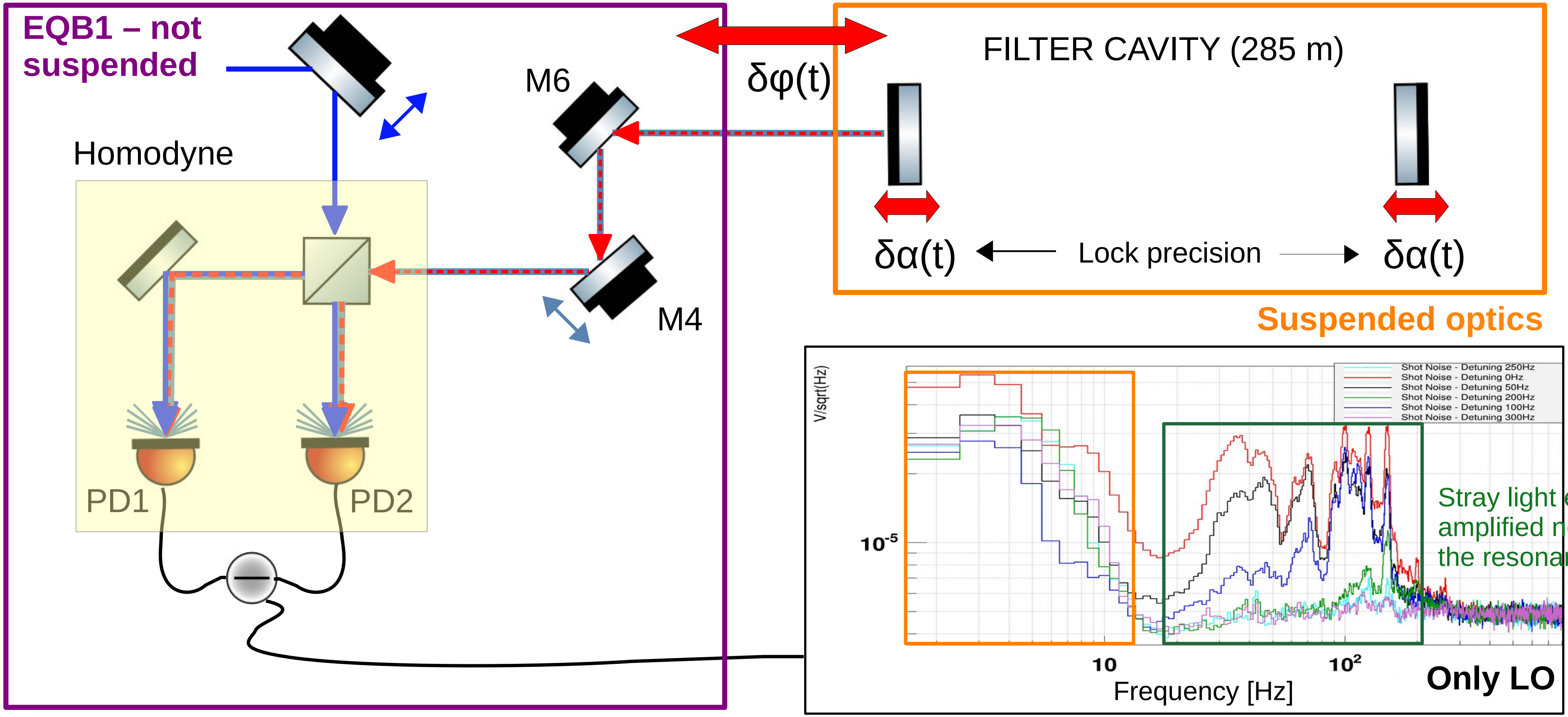
- amplitude of round-trip optical path length fluctuations for the interfering stray light: ~10-15 fringes, i.e. ~10-15 μm round-trip;
- typical period of optical path length breathing: around 1.5÷2 s;
- the interfering stray light is about 10^{-10} of the LO power, i.e. 50 fW.

This value is compatible with the expected scattering from HQE photodiodes assuming the 50 ppm BRDF at 20 deg, since the beam waist radius on photodiodes is around 15 μm.

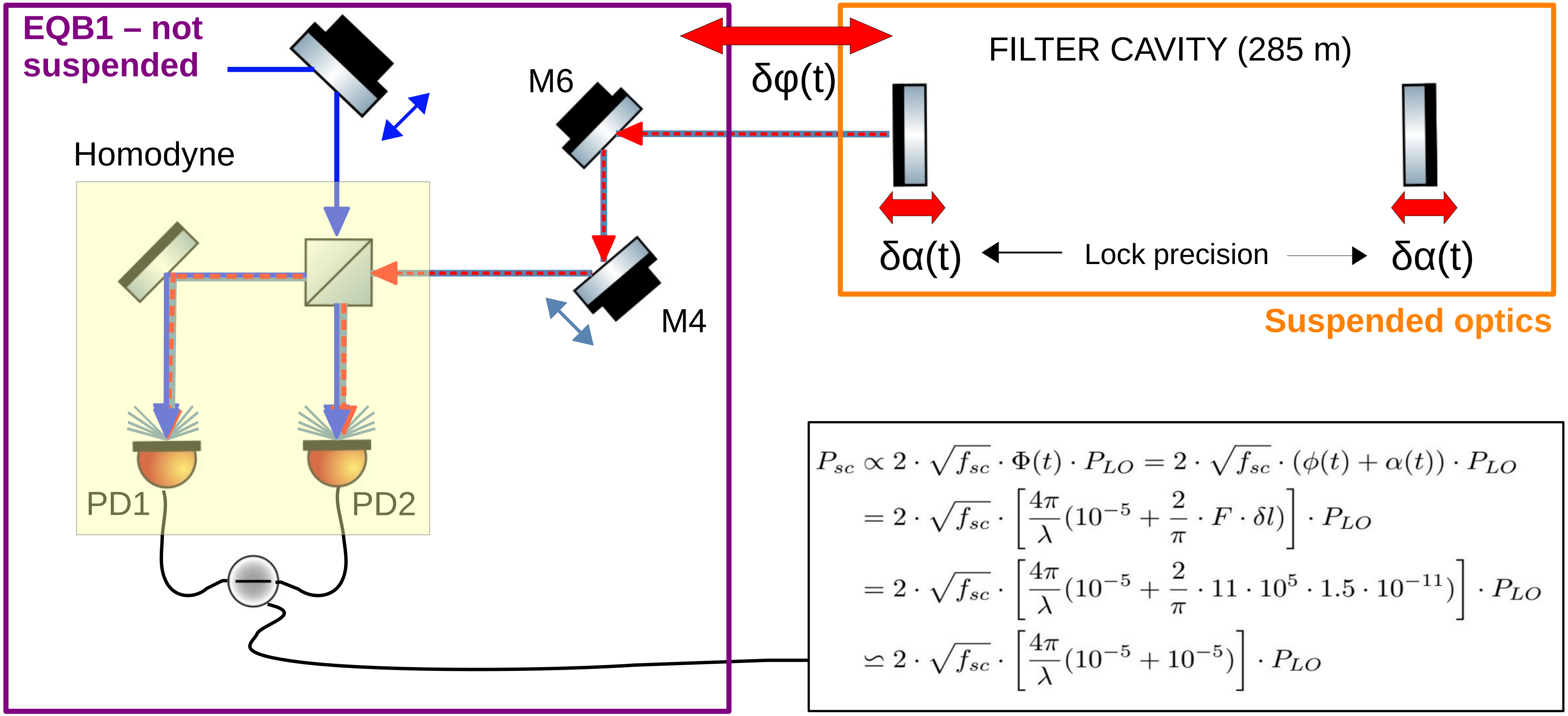
Filter cavity out of resonance



Filter cavity close to resonance



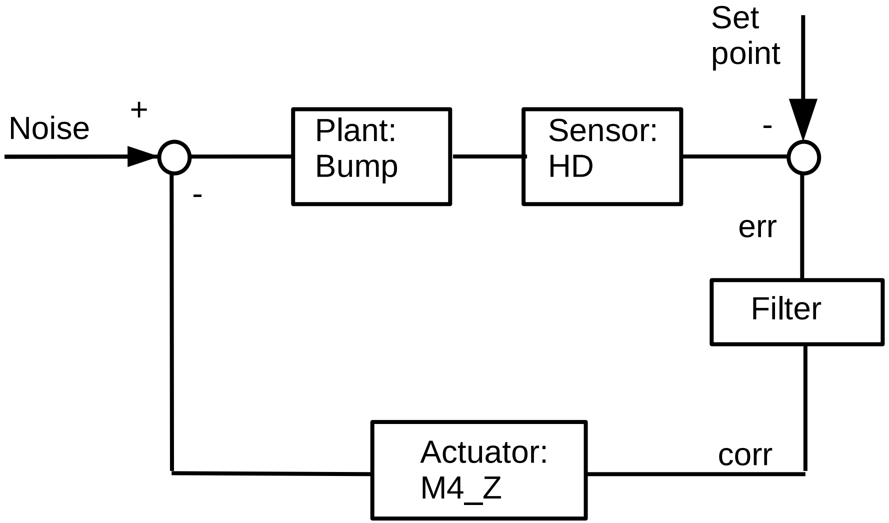
Filter cavity close to resonance

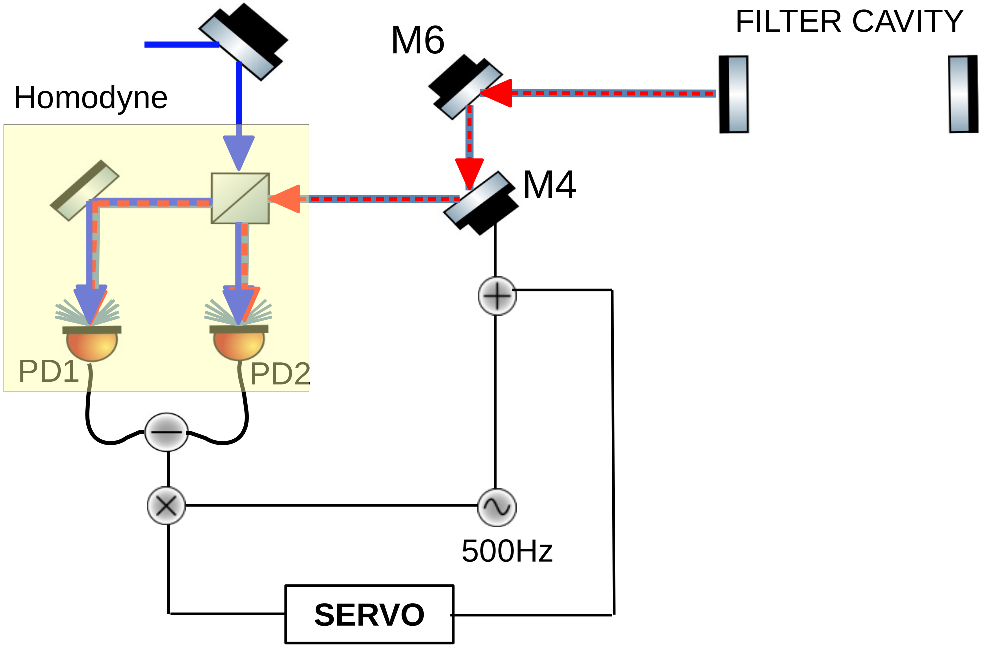


$$
\begin{aligned}
P_{sc} &\propto 2\cdot\sqrt{f_{sc}}\cdot\Phi(t)\cdot P_{LO} = 2\cdot\sqrt{f_{sc}}\cdot(\phi(t)+\alpha(t))\cdot P_{LO}\\
&= 2\cdot\sqrt{f_{sc}}\cdot\left[\frac{4\pi}{\lambda}(10^{-5}+\frac{2}{\pi}\cdot F\cdot\delta l)\right]\cdot P_{LO}\\
&= 2\cdot\sqrt{f_{sc}}\cdot\left[\frac{4\pi}{\lambda}(10^{-5}+\frac{2}{\pi}\cdot 11\cdot 10^{5}\cdot 1.5\cdot 10^{-11})\right]\cdot P_{LO}\\
&\backsimeq 2\cdot\sqrt{f_{sc}}\cdot\left[\frac{4\pi}{\lambda}(10^{-5}+10^{-5})\right]\cdot P_{LO}
\end{aligned}
$$

Stray light active loop

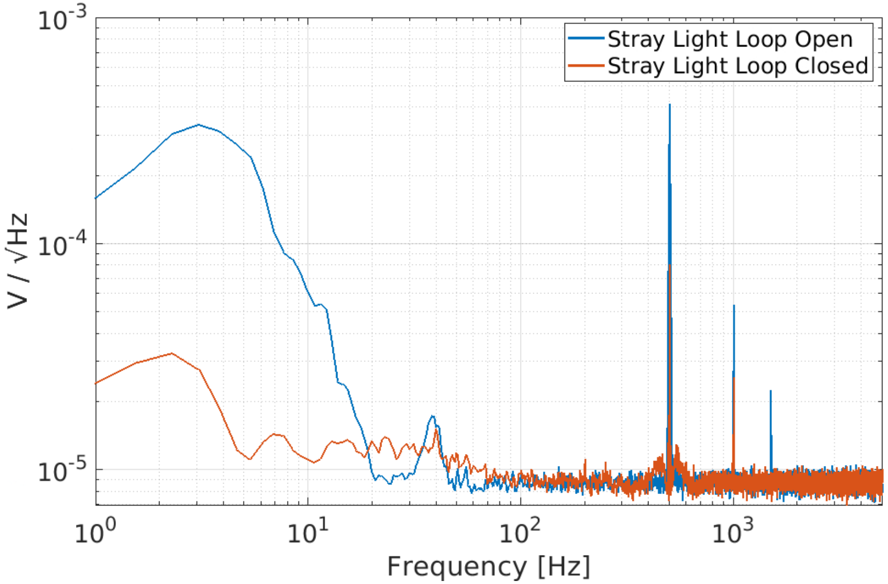
Plant : difference in phase (optical path) between LO and scattered field
Sensor : HD DIFF AUDIO channel demodulated at dither line frequency
Actuator : mirror on scattered light path M4_Z (and M6_Z with high seismic activity)



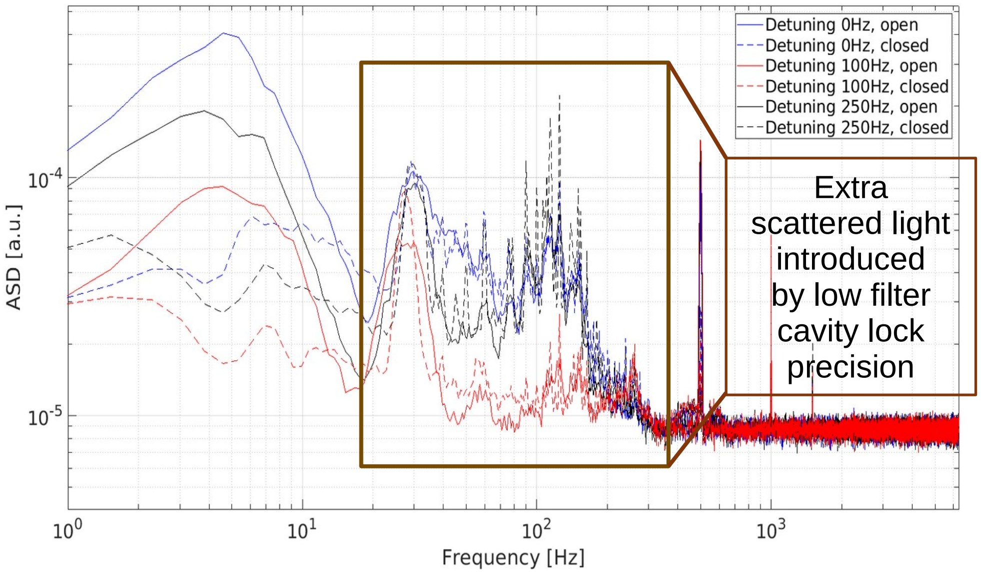


Stray light loop closed only with LO, low lock precision of FC

Filter cavity out of resonance:

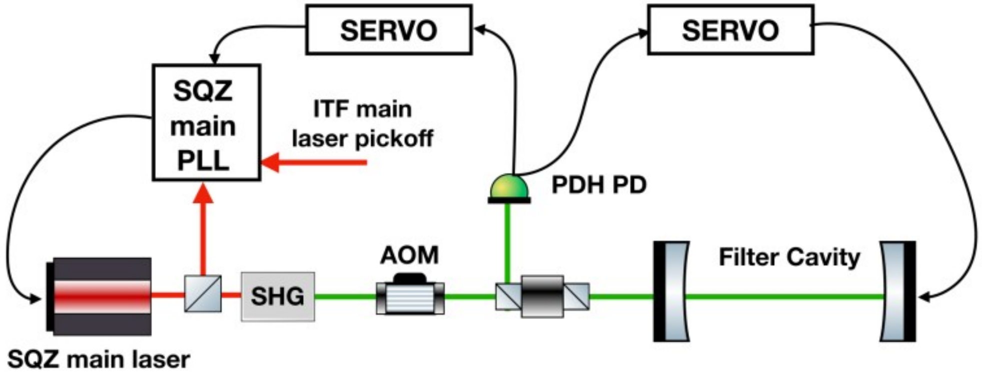


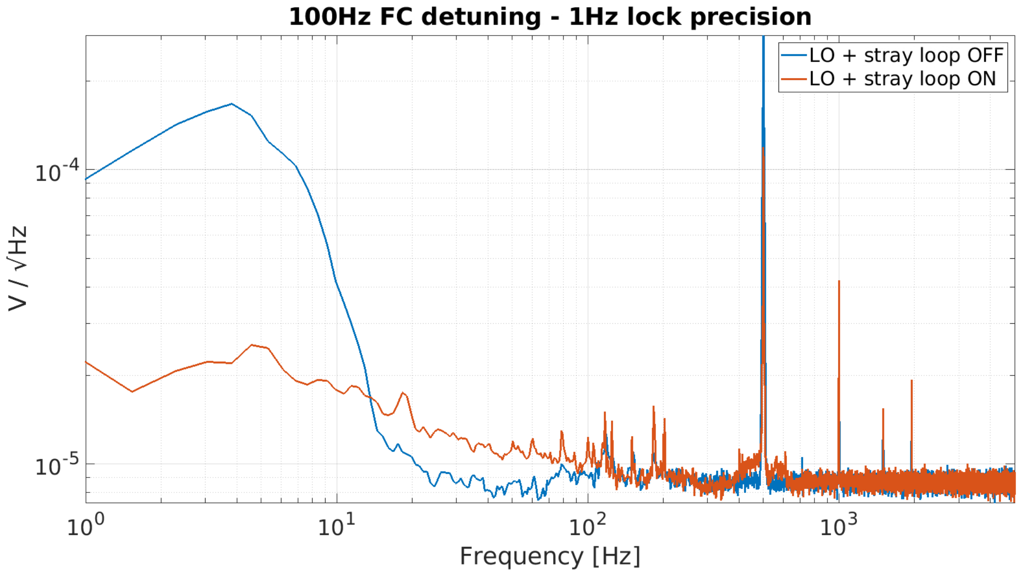
Filter cavity on/close to resonance:



The filter cavity is locked acting only on the cavity end mirror. **Lock precision ~10Hz.**

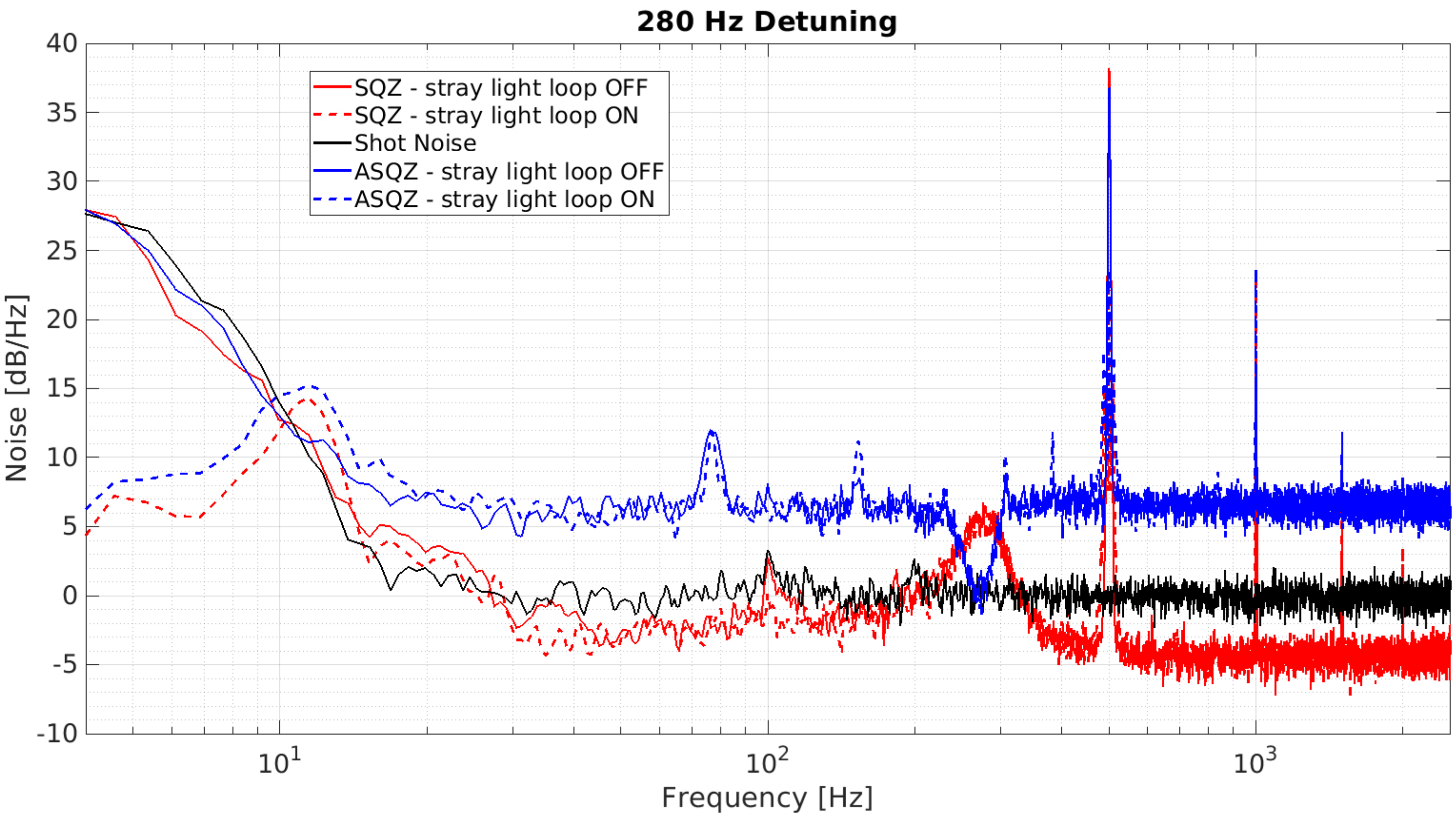
Stray light loop closed only with LO, high lock precision of FC



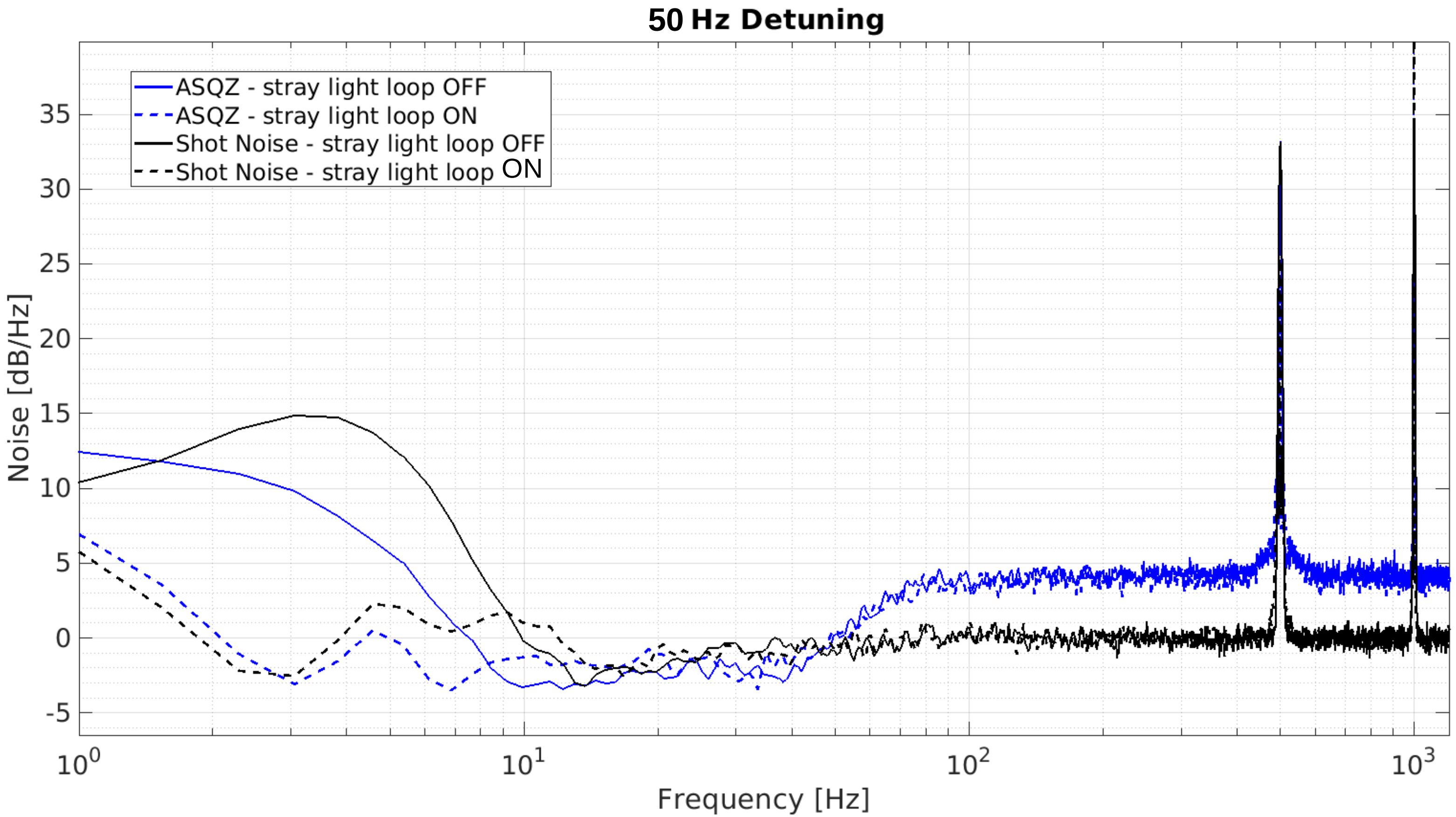


The filter cavity is locked acting on the cavity end mirror and the laser frequency.
Lock precision < 1Hz.

Coherent Control + Stray light loop



Coherent Control + Stray light loop



Conclusions

- We performed a ghost beam mitigation campaign in AdV+
- We developed a set-up to directly measure the scattering produced by optics
- We are able to reduce the stray light using feedback control loop
  - Passive mitigation planned : Faraday Isolator before homodyne

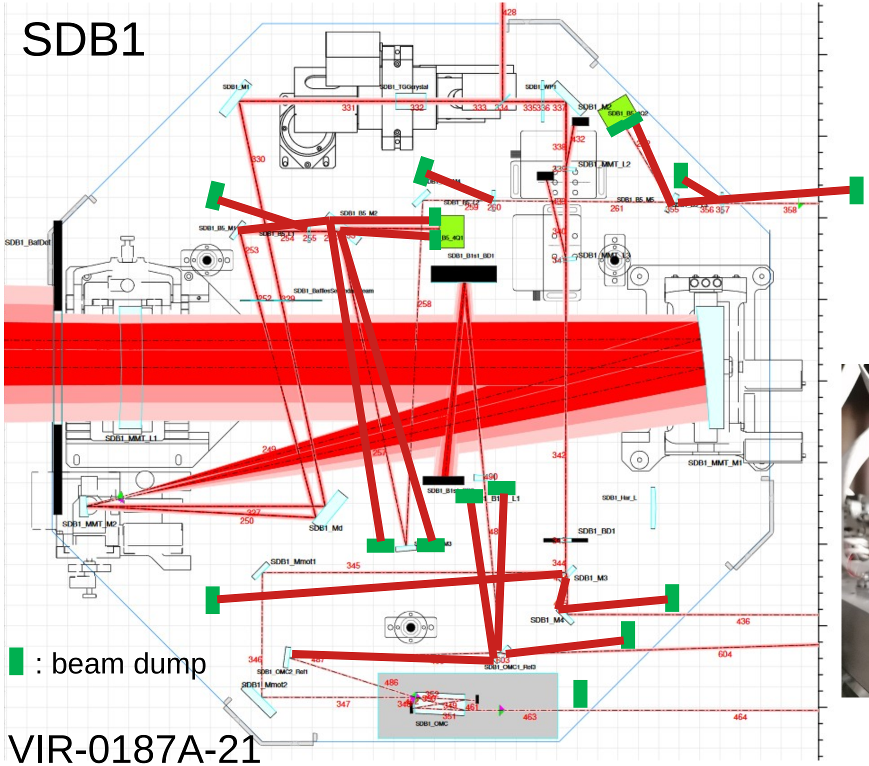
Next steps:

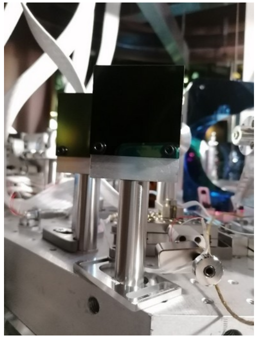
- See the results of the mitigation on the O4 Virgo sensitivity curve

EXTRA SLIDES

Ghost beams systematic study

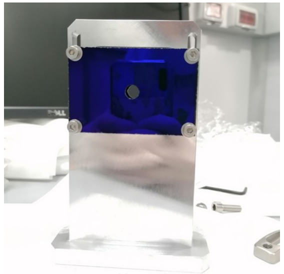
DET system: suspended bench SDB1



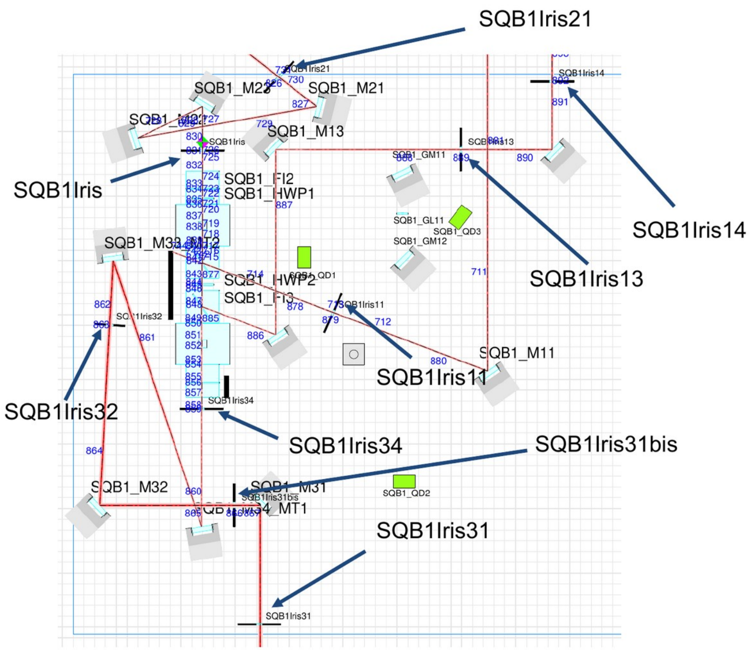


: beam dump

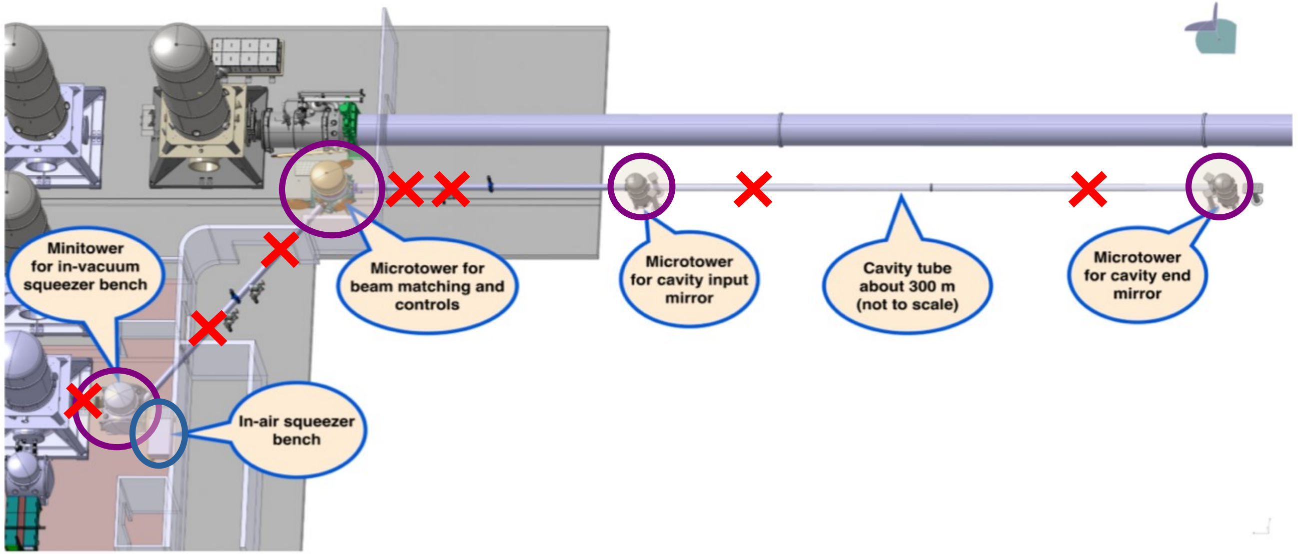
FDS system: suspended bench SQB1



: diaphragm



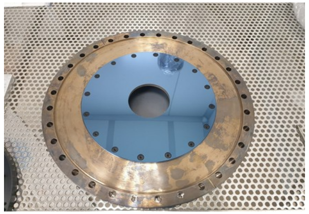
Stray light on FDS system



: not suspended bench EQB1

: suspended optics (benches and mirrors)

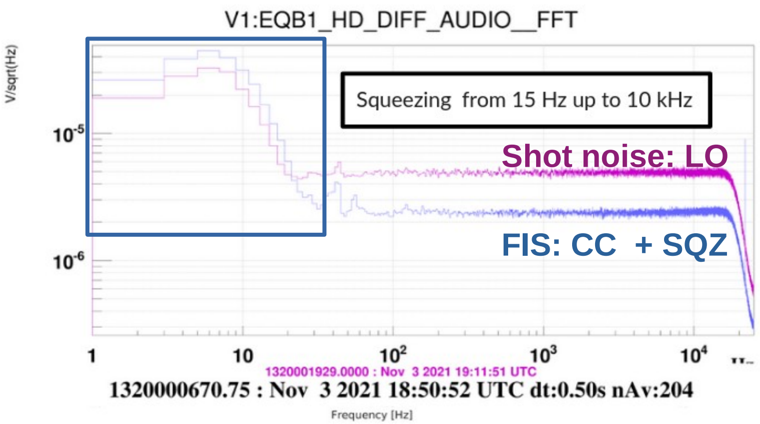
: baffles



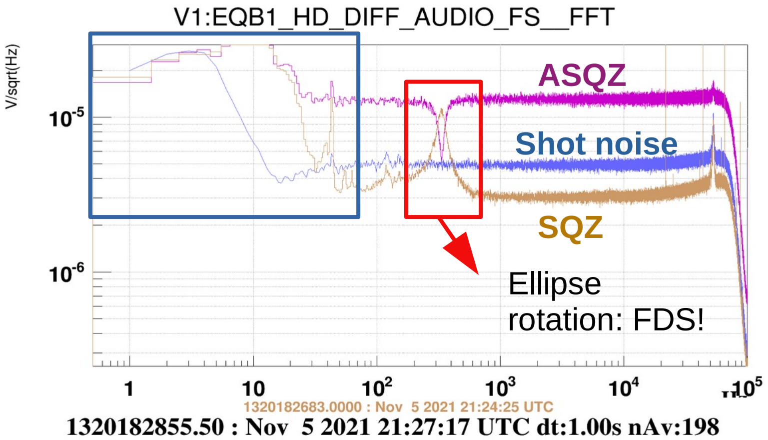
Credit to IFAE

Stray light bump in different configurations

1. FIS from SQB1



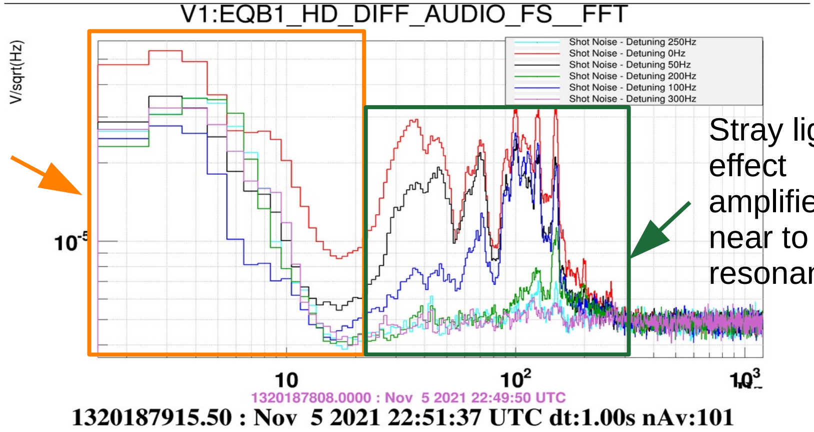
2. FDS (reflection from FCIM)



Ellipse rotation: FDS!

3. Shot noise from FCIM with different FC detuning

Stray light bump at low frequency



Stray light effect amplified near to the resonance

Stray light bump mitigation strategies

Passive strategies:

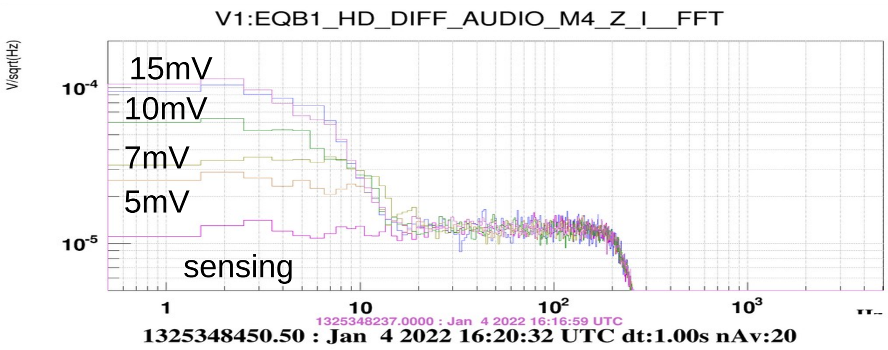
- Improve tuning of HWP in the EQB1 Faraday Isolator
- Fine tuning of HD photodiodes alignment
- Irises in front of HD photodiodes
- QWP in front of HD photodiodes
- Increase the size of the beam arriving on HD photodiodes (to be done):
  - Beam size at the PD: w(z) ~ w0 ~ 15 um
  - $f_{sc} \sim \dfrac{BRDF \cdot \lambda^2}{\pi \cdot w(z)^2}$ ~ 8e-8
  - Shift the PD along z to have a bigger w(z)
  - Change the HD telescope and replace photodiodes by larger ones
- Put a Faraday Isolator before the HD to attenuate the stray light effect (to be done)

Active strategy:

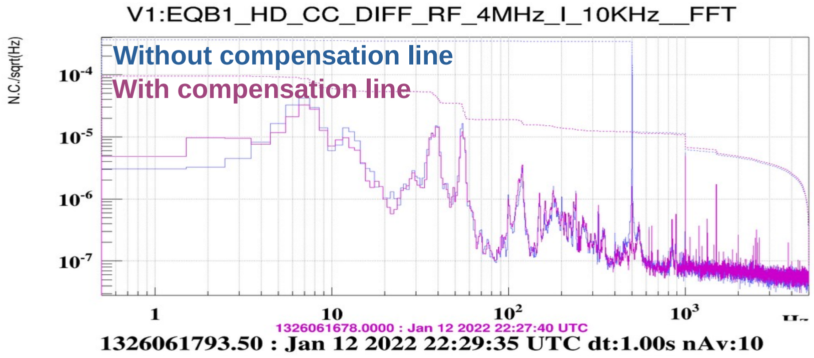
- Feedback loop to mitigate the stray light bump acting on the phase of the back-scattered field

Loop closed: LO back-scattering toward FCIM, FC out of resonance

- Dither line amplitude optimized: A ~ 15 mV

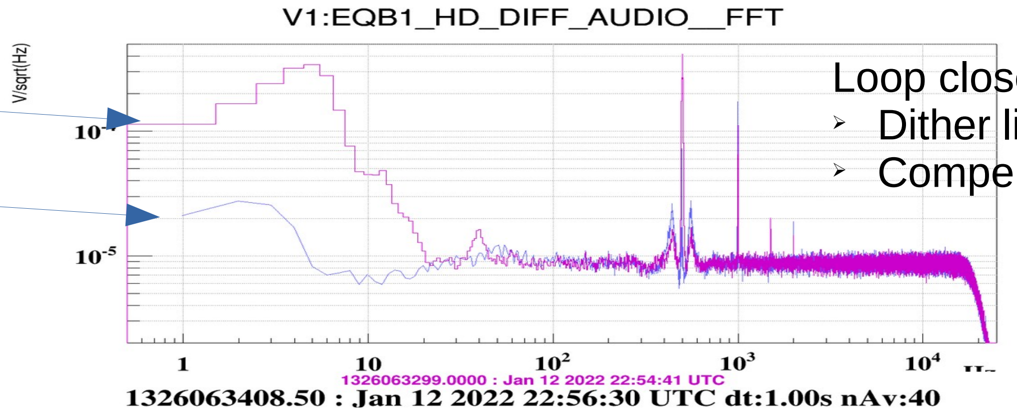


- Compensation line on LO_M2



Loop open

Loop closed



Loop closed:
- Dither line 500Hz, 15mV
- Compensation line 500Hz, 100mV